ELECTRO-CHEMICAL SPARK MACHINING (ECSM) OF ALUMINA AND QUARTZ

by

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ELECTROCHEMICAL SPARK MACHINING (ECSM) OF ALUMINA AND QUARTZ

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1996

CERTIFICATE

It is certified that work contained in this thesis entitled ELECTROCHEMICAL SPARK MACHINING (ECSM) OF ALUMINA & QUARTZ, by **Sanjay Kumar Chak**, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

8^{th}May 1996.

Prof. V.K. Jain
Department of Mechanical Engineering
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Dedicated To

MY PARENTS

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(Sanjay Kumar Chak)

Abstract

Electrically non - conducting hard and brittle materials like Alumina (Al_2O_3) and Quartz are becoming popular because of their inert nature and specially required in advanced industries like nuclear and aerospace engineering industries. Machining of these kind of materials by conventional processes is not possible; even ECM and EDM processes are unable to machine this class of materials because they are electrically non - conducting. However, machining on these materials is possible by Electro - Chemical Spark Machining (ECSM) Process, a new process which is being developed in the labs.

The work attempted in this thesis is the **machining of electrically non - conducting hard, brittle and high temperature resistant materials by employing ECSM process using eccentrically rotating gravity feed tool.** So far, only solid stationary or truly rotating (zero eccentricity) tool is used by previous researchers and the results obtained by them are not very encouraging. However, ECSM itself has got its own limitations, such as, limiting depth characteristic, upward shifting of spark zone during machining, etc.

In the present work orbital rotation of the tool (trepanning action) with gravity feed has shown the encouraging results. We have been able to make a through hole in Quartz sample (thickness = 2.35 mm) in only 14 min. and the maximum depth achieved is 4.21 mm in 30 min test. However, in the case of Alumina maximum depth achieved is 1.35 mm in 30 min test. During experimentation it is observed that, beyond a certain value of electrolyte temperature the process performance deteriorates.

SEM photographs present the clear view of machined profile and it is observed that machining of such materials is carried out by melting and chemical etching process [19].

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Chapter 1

Introduction

Machining of very hard, brittle, high temperature resistant, non-conducting materials such as borosilicate glass, quartz, ceramics (ZrO_2, Al_2O_3) is a serious problem yet to be resolved. Such materials are required mainly in nuclear and aerospace engineering industries, because metals cannot provide the requisite qualities. Other methods such as Ultrasonic machining(USM), Abrasive jet machining(AJM), Laser beam machining(LBM), Electron beam machining(EBM) etc. can also be used for machining such non-conducting materials, but the surface finish, surface integrity, dimensional accuracy and economics are some of the aspects to be investigated. Another process i.e. electrochemical spark machining is also being developed for the same purpose.

Electrochemical spark machining (ECSM) is a hybrid process that involves machining by sparking (not by other discharge) and electrochemical action, hence more appropriately known as electrochemical spark machining process (ECSM). It is useful for machining non-conducting materials. In this process sparking takes place in an electrolytic cell across a bubble. The voltage applied across the electrodes is more than 30 V. Unlike ECSM, EDM and ECM are used for machining electrically conducting materials, and from the point of view of material removal, accuracy and surface finish, these two methods have maximum potential. Unfortunately these processes can't be used for machining non-conducting materials,

so this hybrid process is being developed and the interesting results have been obtained during the experimentation.

Few kinds of experiments have already been done successfully i.e. drilling by the rotating tool on borosilicate glass, engraving on glass by using a ECD pen [1, 2, 9, 13], and slicing by TW-ECSM on partially electrically conducting materials (piezo-electric materials (PZT) and carbon fiber epoxy composites) and non - conducting materials like glass (Soda lime, Silica and Borosilicate) and ceramics (Al_2O_3, Si_3N_4 and SiC) [10, 14, 17, 20,].

Effective and Economic machining (drilling by trepanning method) on Quartz and Alumina Al_2O_3 is a matter of current topic, so an attempt has been made to exploit the full potential of ECSM process for machining newer non-conducting and brittle materials like quartz and Al_2O_3 successfully by electrochemical spark trepanning (ECST) method.

Electrochemical arc machining (ECAM) and Electrochemical spark machining (ECSM) are comparatively new developments and are not popular among the shopfloor engineers. This is so as these processes are still in the developmental stage and need further study to have a better understanding.

1.1 Electrochemical Discharge Phenomenon and its Mechanism

Electrical discharges can take place in an electrolyte system when a high electric field is set across a bubble. The mechanisms causing high filed can be due to:

1. Electrolytic gas created at the surface of the electrodes,

2. Growth of the layers of low ionic concentration near the electrodes and formation of partially conducting oxide films on the anode surface,

3. Local stagnation of flow,

4. Vapor blanketing of electrode surfaces,

5. Particles present in the electrolyte.

First consider the different phenomena an electrolytic system can exhibit under the influence of an applied voltage pulse. These are as follows:

1. Electrochemical action without any electrical discharge;

2. Electrochemical action followed by discharge between an electrode and electrolyte; and

3. Electrochemical action followed by discharge between electrodes.

Fig (1.1) shows these three situations schematically.

Case (1) can be called as the normal ECM condition in which material removal takes place due to electrochemical dissolution. Case (2), that is, the kind of situation indicated in Fig (1.1b) arises when a sufficiently high electric field exists across a gas bubble or a non-conducting layer in an electrochemical set-up. The sparking, which are thus generated, can be used for thermo-mechanical material removal even if the work material is not electrically conducting. This process is called ECSM.

Case (3), that is, the kind of situation indicated in Fig (1.1c) arises generally when the discharge produced between an electrode and electrolyte grows in size and bridges the gap between the electrodes. This is possible only if the inter-electrode gap is small enough (<100um). In this situation, material removal from the work electrode takes place due to both electrochemical dissolution and thermo-mechanical action. Due to the continuous sparking (i.e. arcing) all over the electrode, this process is called electrochemical arc machining ECAM [3, 8].

Generally a simple electrochemical cell consists of two electrodes dipped in an electrolyte tank (Fig 1.2a). When an external potential is applied between the

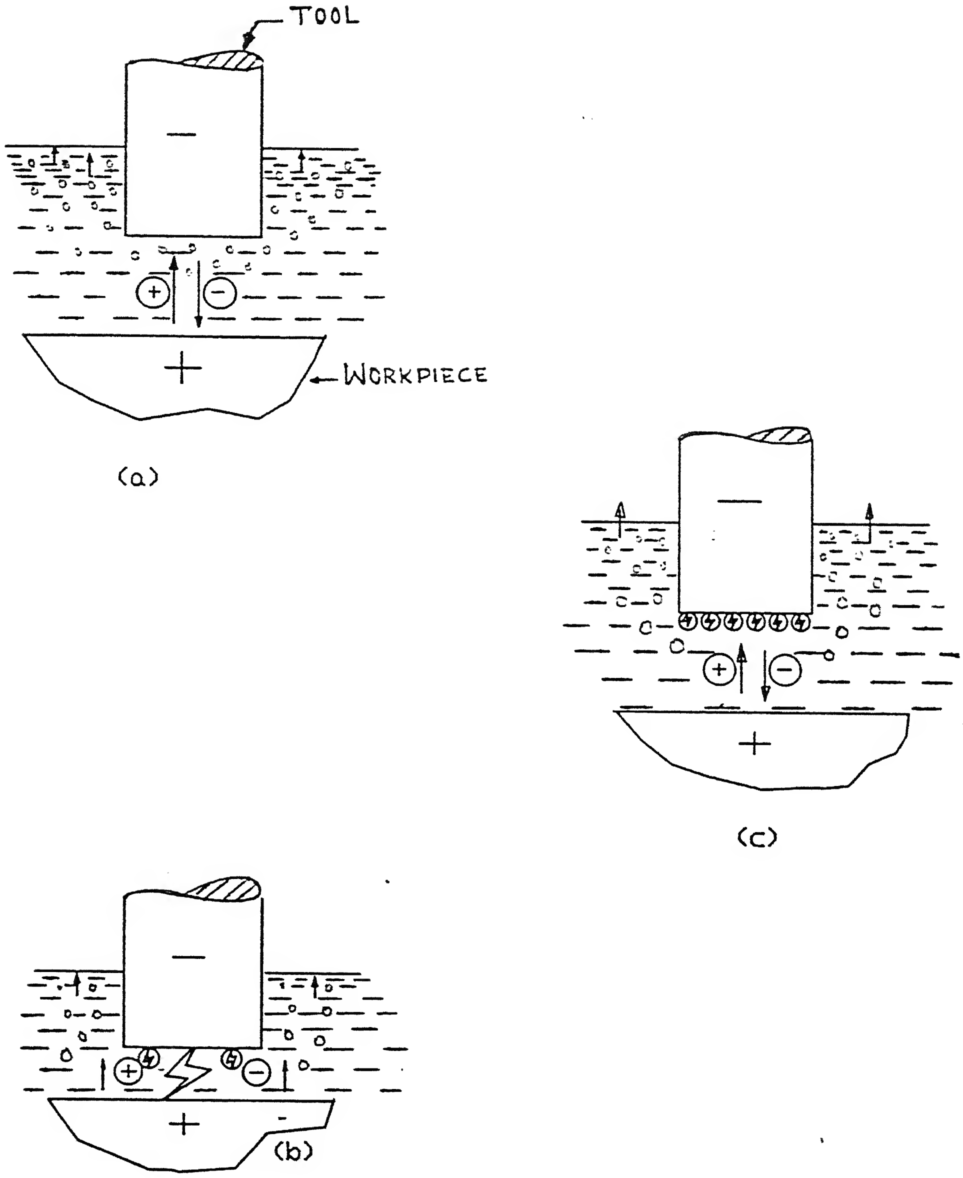


Figure 1.1: Different situations an electrolytic system can exhibit under the influence of an applied voltage pulse, [8]

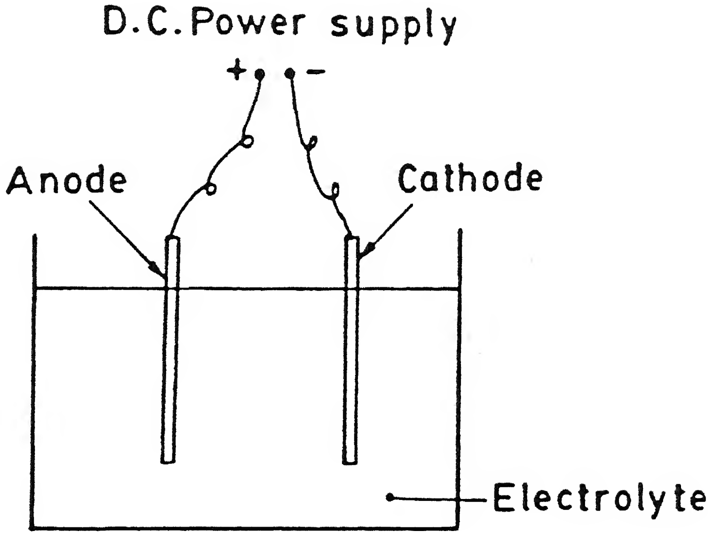
electrodes, current passes through the cell resulting in electrochemical reactions, such as anodic dissolution, cathodic deposition, electrolysis of the electrolyte etc., depending on the electrode - electrolyte combination.

Thus, if a suitable electrolyte is chosen and the electrodes are of grossly different sizes (Fig 1.2b) then, beyond a certain value of the applied potential, electric spark appears at the bottom edge of the smaller electrode and the cell current drops. This phenomenon is known as electrochemical discharge (ECD) phenomenon.

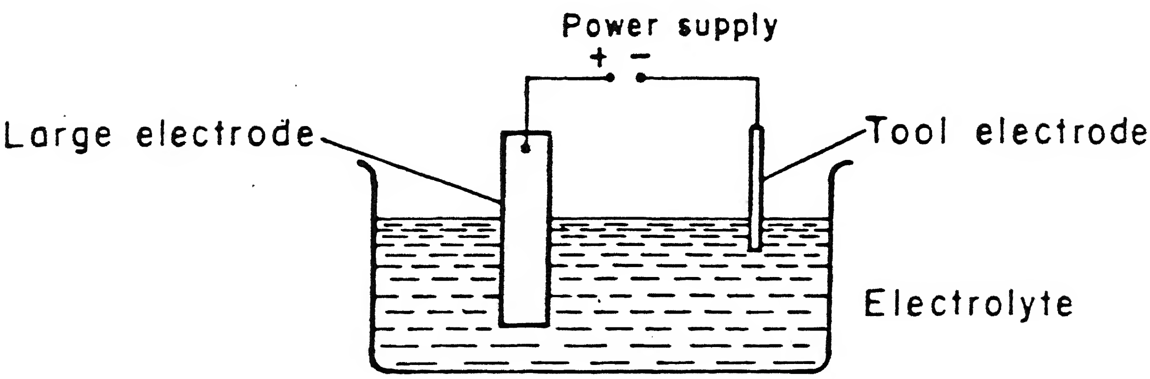
The observation of this process have established the fact that the discharge between electrode and electrolyte takes place due to bubble generation because of electrochemical reaction and thermal process (Fig 1.3) .

When a sufficient high potential exists i.e. (beyond a certain value of applied potential) across a gas bubble or a non-conducting layer in between electrode and electrolyte, electrical discharge appears at the smaller tool electrode . Thus the hydrogen gas bubble blanketing of the tool electrode (cathode) due to chemical reaction and water vapor formation is found to be the primary reason for discharge initiation between electrode and electrolyte.

The contact area between the electrode and electrolyte is constricted by bubble nucleation on the electrode surface causing the non-uniformity in the current path. These bubbles grow in size with time and cause an increased resistance at the region, the ohmic heating of the electrolyte becomes significant because of which bubbles blow off. Consequently, the current through the circuit drops to zero within very short time span, which is analogous to the switching off in an electrical circuit and discharge takes place along the locations of the bubble bridges [5].

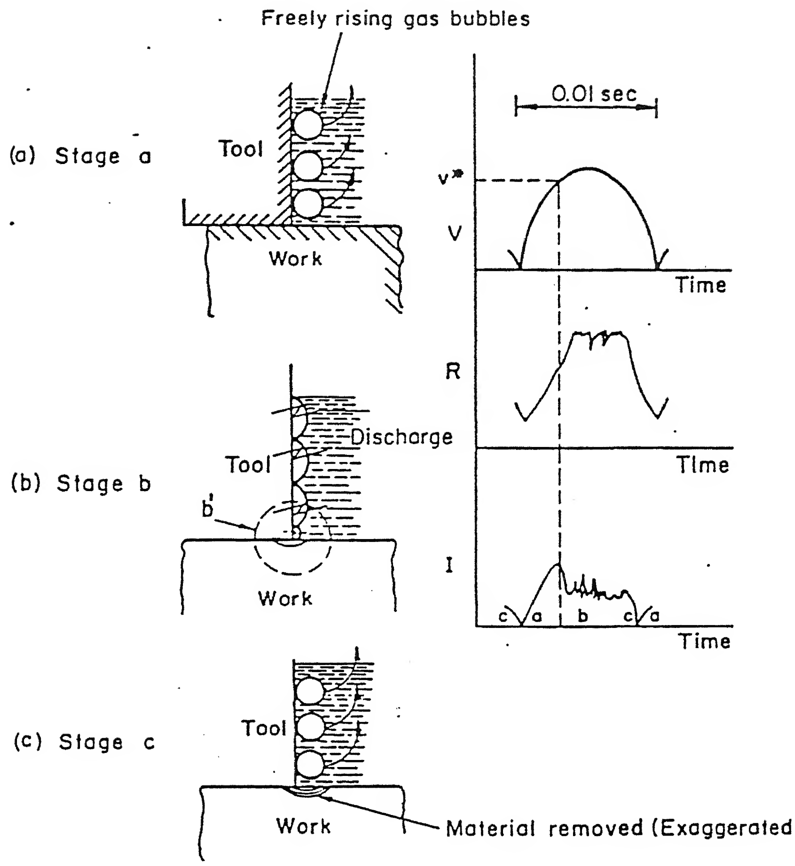


(a) Electrochemical cell



(b) schematic diagram of ECD set up.

Figure 1.2: Schematic diagram of ECD cell



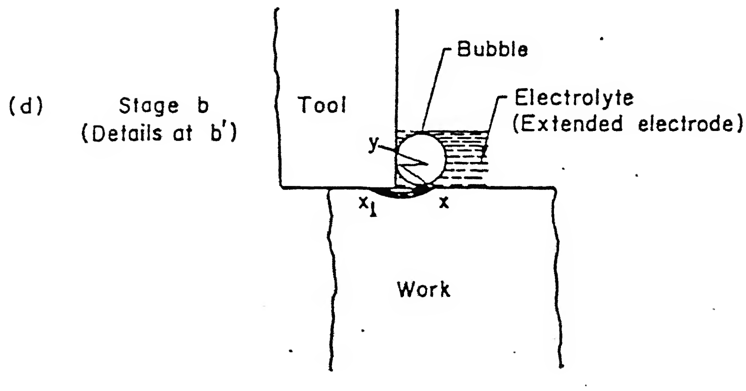


Figure 1.3: Mechanism of material removal, [1, 3]

1.2 Machining Of Non - Conducting Materials by ECSM Process

The general setup required for machining non conducting materials is shown in (Fig 1.4). Copper wire used as tool, is one electrode and graphite rod is another electrode, and both are placed near to each other in the electrolytic solution. Tool is in contact with the workpiece by its gravity. When the applied voltage exceeds the saturated voltage[1], bright spark appears, which thermally erodes the material from the non conducting workpiece. Material removal rate mainly depends upon applied voltage, electrolyte concentration, electrolyte temperature, tool polarity, workpiece material etc.

The basic mechanism of material removal is suggested as thermal erosion and it is claimed by various researchers [1, 4, 5, 6, 13, 19, 21], the heat energy released by the tool electrode during discharge, partially heats the local region such that the temperature of the local region exceeds the melting point of the material and due to high thermal shocks caused by discharge forms a small crater beneath the tool.

By experiment it is clearly understood that the sparks appear at the vicinity of the tool edge and as the voltage is increased the region of sparking zone enlarges, due to which unmachined portion (center region) of workpiece shrinks. Simultaneously, the sparking zone also spreads along the side of the tool. Figure (1.5) shows the region of thermal erosion and final shape formation of crater [9].

1.3 Survey Of Previous Work

Electrochemical spark, during electrolysis of molten NaCl at high current density, was first observed by Taylor [18] in 1925, at the anode tip and was termed as

[1]voltage at which spark just appears

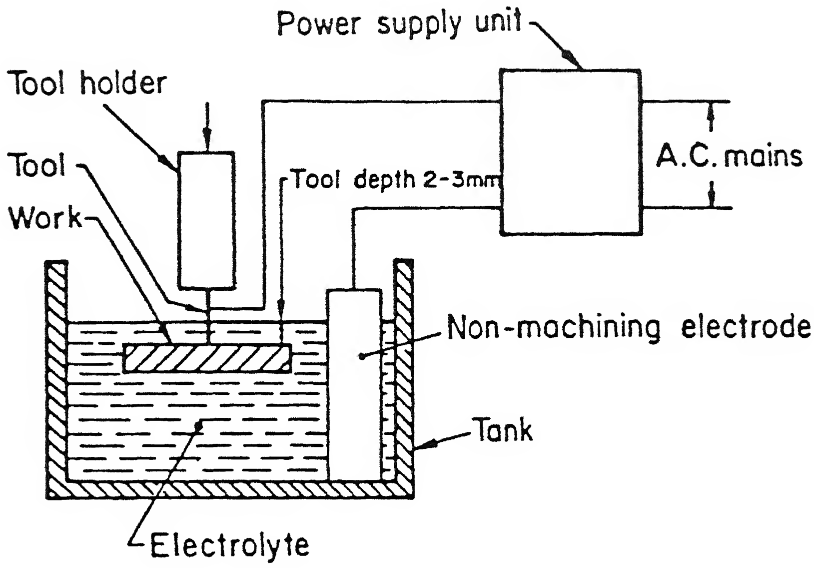


Figure 1.4: Configuration of non - conducting work machining using ECSM, [9]

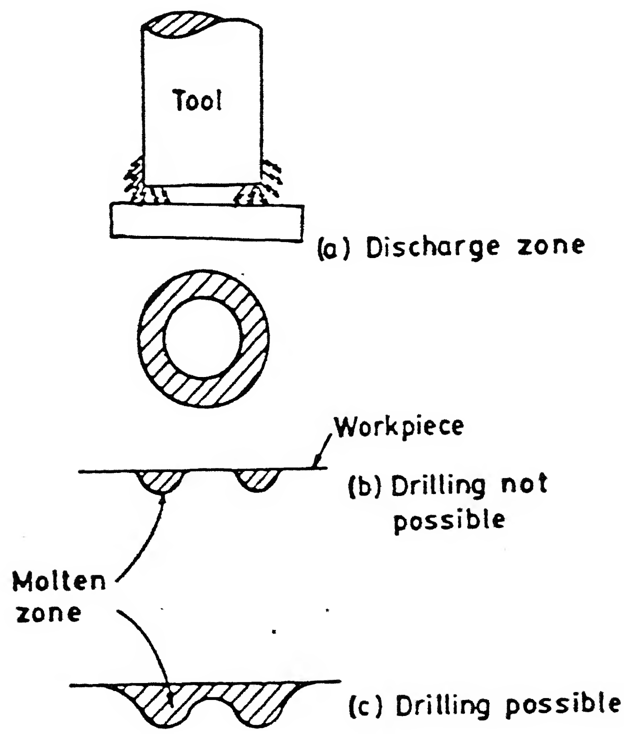


Figure 1.5: Drilling by ECSM; [9]

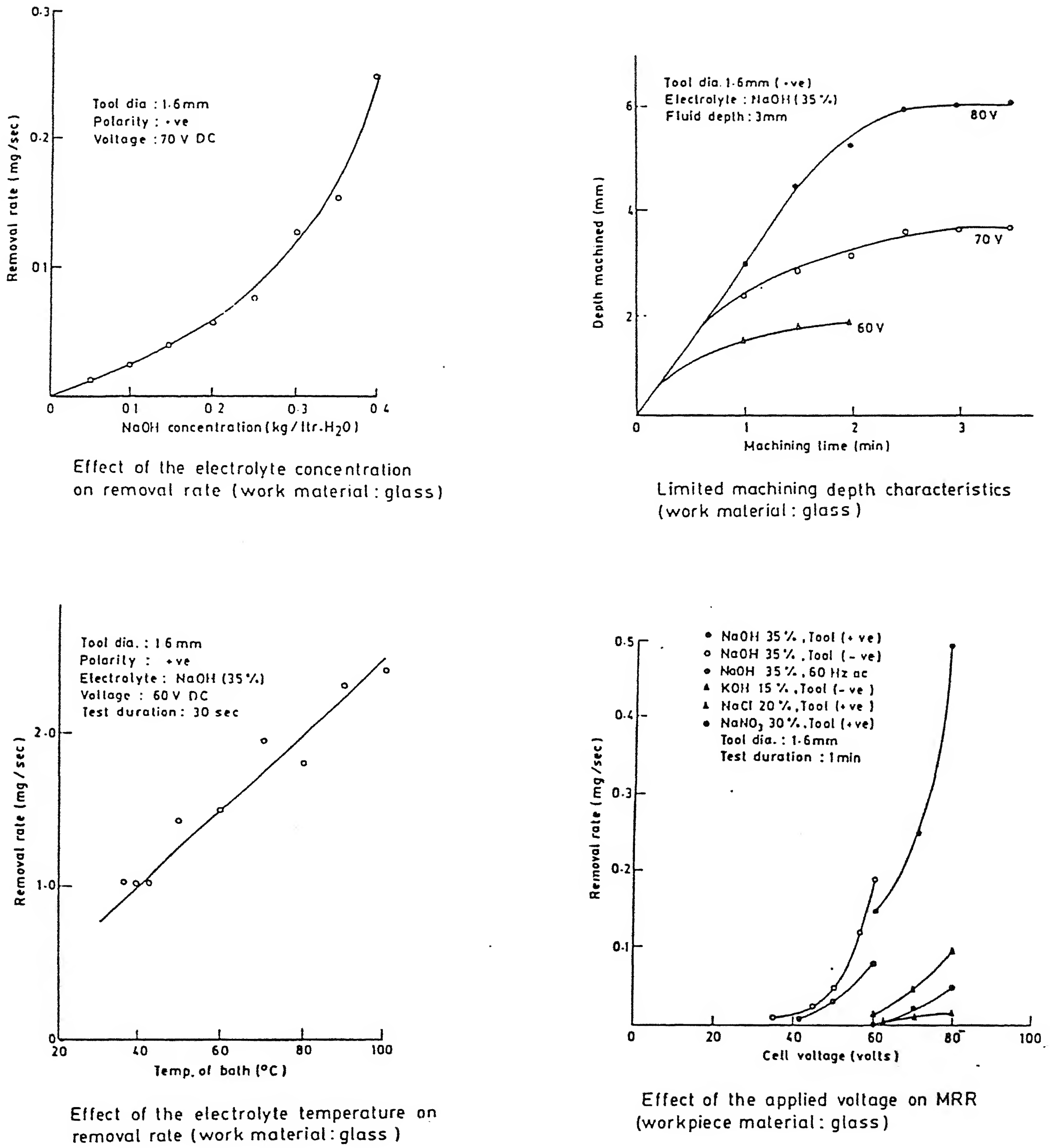
"Anode effect". Later Kellog [11] in 1950, showed that similar phenomenon can occur at the cathode, and in aqueous electrolyte also. Electrochemical discharge between tool and workpiece was also observed during the attempts for enhancing MRR in ECM by the application of higher potential between the electrodes, and was considered as detrimental factor because it damages both the tool and workpiece surfaces.

The phenomenon of electrical discharge in electrolyte was first utilized by Kurafugi and Suda [13] in 1968. They drilled holes upto the depths of 0.31mm in a glass workpiece with 15% NaOH electrolyte and cell voltage of 34 volts.

Cook, Foot, Jordan and Kalyani [6] in 1973 conducted experiments on ECD for machining glass and other non - conducting materials and identified the process to be polarity dependent and electrolyte sensitive. Machining rate increases with concentration and temperature of electrolyte, but for a given voltage the rate of machining was found to decrease with time. The corresponding results are shown in (Fig 1.6). They concluded that the possible mechanism of material removal in ECDM could be attributed to the thermo mechanical, chemical, electric field and due to some other unknown effects. Experiments were conducted with D.C. pulsed power supply. With pulses in micro second range, it was found that MRR increases by a factor of two. Also, surface produced by pulsed power was found to be much smoother than a D.C. power supply.

Umesh kumar [21] in 1985 did the similar kind of experiments with negative tool whereas Cook et.al [6] concentrated on the positive tool. He noticed that discharge vanishes partially with flowing electrolyte. He suggested the mechanism of material removal as thermo-mechanical and electro-chemical actions.

Allesu [1] in 1988 conducted extensive experiments on ECS phenomenon and ECSM process. He suggested that the mechanism of material removal depends on thermal heating, cavitation and electro-chemical action. He explained the reason



Effect of the electrolyte concentration on removal rate (work material: glass)

Limited machining depth characteristics (work material: glass)

Effect of the electrolyte temperature on removal rate (work material: glass)

Effect of the applied voltage on MRR (workpiece material: glass)

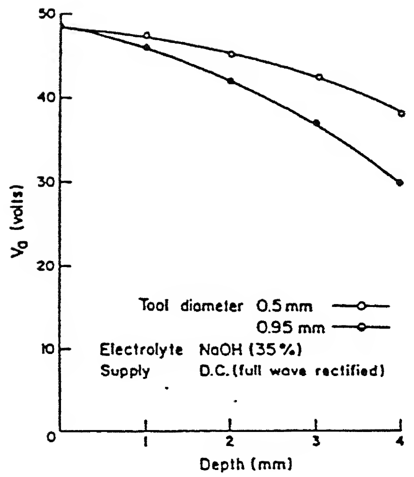
Figure 1.6: Parametric study of ECDM process during machining on glass, [6]

for limiting depth characteristic as a result of loss of potential between the tool electrode and bulk electrolyte with the tool penetration in the workpiece.(Fig 1.7a). This is caused by the accumulation of gas bubbles, machined debris and electrolyte under confined conditions inside the hole. He reported discharge voltage to increase with increase in flow of electrolyte (Fig 1.7b) and upward shifting of the discharge zone when tool penetrates the workpiece(Fig 1.7c). Perhaps, the most useful observation made by him was the distribution of voltage drop in ECDM process(Fig 1.7d).

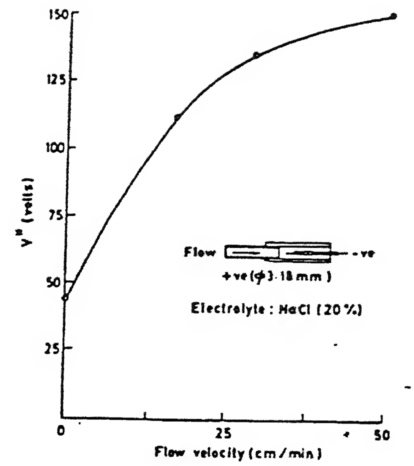
Indrajit Basak [5] in 1991 has done experiments on the machining of glass using ECSM process with different electrolyte such as NaOH, KOH, NaCl and different power supply such as smooth D.C. and 100Hz full wave rectified D.C. He showed the V - I characteristic for different electrolytes, tool diameters, tool depths, and concentration of electrolytes (Fig 1.8). Effect of inductance on external was also studied by him and it was observed that MRR can be increased by 200% by introducing inductance in the circuit. He concluded that electrical discharge takes place due to switching action, and not due to dielectric break down of the medium. While the study of relation between voltage and current in ECSM process is done by various researches [1, 2, 3, 5, 7, 16].

Recently Naveen Gautam [9] did experiments with different tool kinematics like stationary tool, rotational tool with or without electrolyte flow through it, tool with orbital rotation, and upward movement of the workpiece. He showed that rotation of the tool and flow of the electrolyte through the tool has improved the process performance up to some level. He concentrated on borosilicate glass and did some experiments on quartz.

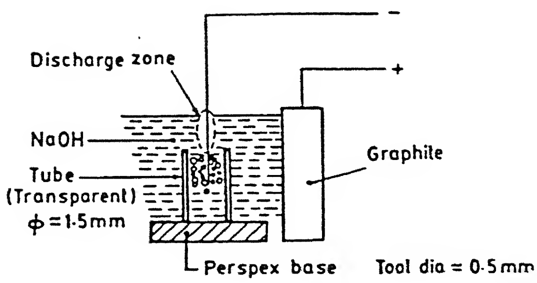
Jain et.al [10] did experimental investigations into traveling wire electrochemical spark machining (TW - ECSM) of composites. They found increase in MRR, tool wear rate (TWR) and overcut with increase in voltage and electrolyte concen-



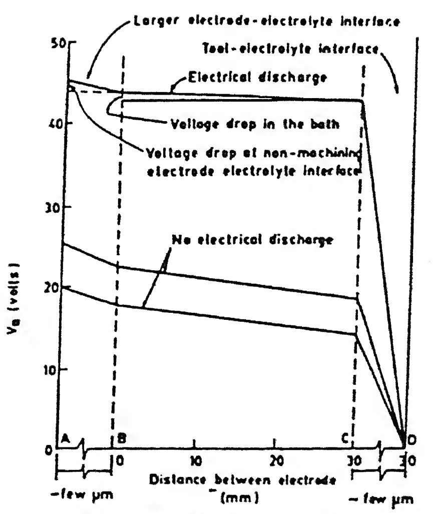
Potential variation along the hole



Effect of the electrolyte flow on V*

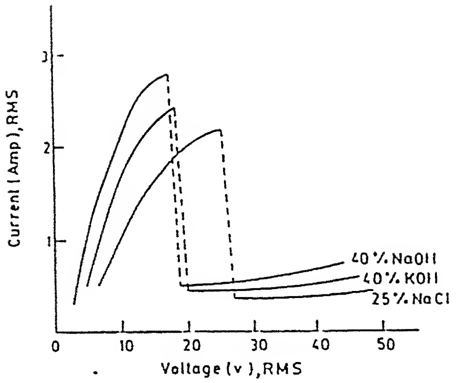


Shifting of the discharge zone



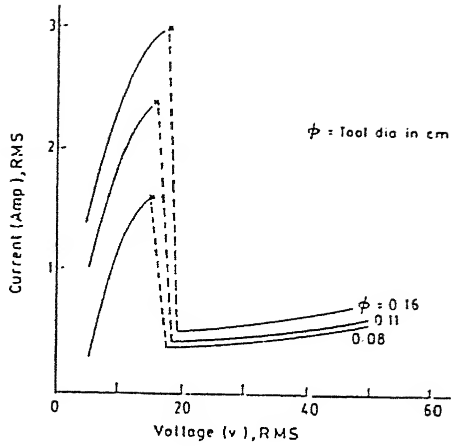
Distribution of voltage drop in an ECDM bath [Electrolyte : NaOH (35 %); Tool polarity : -ve ; Power supply: DC

Figure 1.7: Experimental observation of ECSM process, [1]



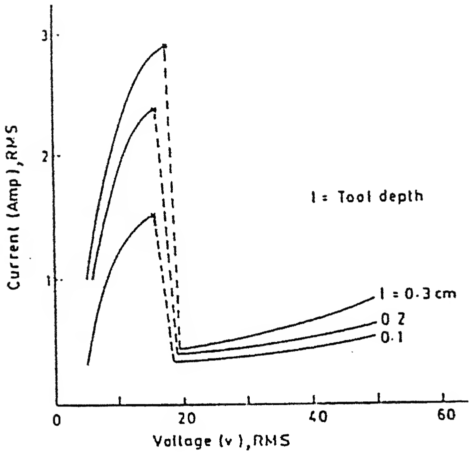
Tool dia : 0·11 cm   Tool depth :=0·2 cm
Power supply : Smooth D.C.

V-I Characteristics for different electrolyte



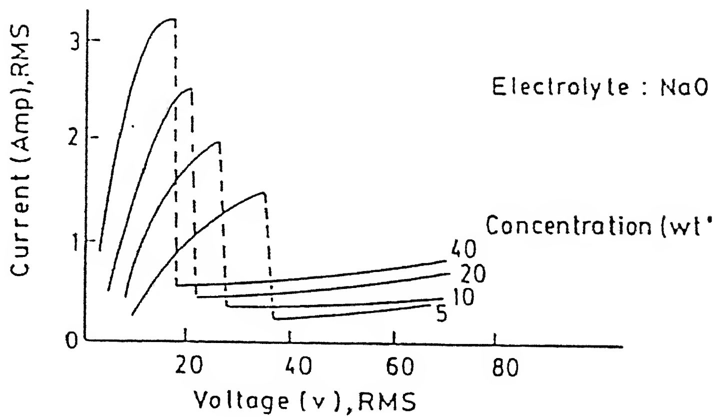
Electrolyte · 40 % KOH ; Power supply · Smooth DC ;
Depth in electrolyte : 0·2 cm

V-I Characteristic for different tool diameter



Electrolyte : 40 % KOH ; Tool diameter : 0·11 cm ;
Power supply : Smooth DC.

V-I Characteristic for different tool depth



Tool dia = 0·11 cm ; Tool depth = 0·2 cm
Smooth DC.

V-I Characteristic for different concentration of electrolyte

Figure 1.8: V - I characteristic for ECSM process, [5]

tration upto 20%. Beyond this value it decreases, primarily because the specific conductance decreases beyond 22.5% concentration value. Effect of bubble was also studied on ECSM process by introducing artificially produced bubbles. It resulted in lower MRR but improved dimensional accuracy.

Raghuram V. et al. [16] did the experiments to investigates the effect of different power supply configurations: rectified DC ; rectified DC with series inductor ; smooth DC ; and smooth DC with a series inductor on electrochemical discharge using NaOH, KOH and HCl. He studied about the behavior of the current with the voltage when smooth DC and smooth DC with inductor is applied.

1.4 Objectives Of The Present Work

Machining of non - conducting materials like Alumina (Al_2O_3) and Quartz by trepanning method to make a hole / cavity by gravity feed tool is attempted for the first time in this work. Materials like ceramics and quartz on which previous work shows very low machining performance due to its peculiar physical properties has been overcome upto certain level by this process.

Almost all researchers [1, 2, 4, 5, 6, 9, 12, 13, 19, 21], have worked with gravity feed stationary tool for drilling operation. Earlier research work has shown that material removal in case of eccentrically rotating tool with few micron gap between the tool and workpiece is higher in comparison to the stationary tool [9]. The explanation is hypothesized for such behavior is discussed in chapter 3.

Our main objective is to enhance the machining rate during the process, by maintaining the optimum cutting conditions throughout the test, like :

1. Max. conductivity at critical Wt%(percentage of NaOH in water where the conductivity is max.) condition.

2. Min. depth of tool in electrolyte to reduce the constriction of current path

in the circuit.

Other objective is to make the through hole in the 100% pure alumina plate of 2.5 mm thickness and quartz of 2.5mm thickness, by maintaining the optimum machining conditions and then to study the geometry and surface integrity of the machined hole by scanning electron microscope.

Chapter 2

Plan Of Experimentation

2.1 Experimental Set-Up

- Experimental set-up shown in (Fig 2.1 and Fig 2.2) is used as Electrochemical spark drilling machine (ECSDM) for the experiments. It was previously designed and fabricated by an M.Tech. student Naveen Gautam, in manufacturing science laboratory, I.I.T Kanpur in 1994. It is used with some modifications such as eccentric rotation of tool and gravity (Fig 2.3) feed for the tool for further investigations in the ECSM process.

  Tool is fitted on the wire vice which is attached to the bottom portion of the adjustable slide. Upper portion of the slide is attached with the rotating pipe which is directly coupled to the stepper motor. Eccentricity of the tool can be adjusted manually as per the requirement. The important requirements kept in mind while designing the tool rotating mechanism are as follows:

  - True rotation of the tool at the desired speed.
  - Continuous electrical supply during tool rotation.
  - Proper insulation of the tool from the various supports and motor.

- Electrical power supply which is used for conducting the experiments is smooth D.C., and is available from the constant current rectifier. Output voltage can be regulated as per requirement. Present experiments were done at three different voltages (i.e. 50, 60, 70 volts) with different electrolyte temperature of NaOH. Experiments at 80 volt could not be done because at this voltage the workpiece showed cracking susceptibility.

- Two independent stepper motors are used with suitable independent "Unistep" controllers for the drive system. One is used for work feed and another is used for tool rotation. Work feed stepper motor is of 12 volt, 20 kg-cm torque and tool rotating stepper motor is of 12 volt, 7 kg-cm torque. Work feed motor is connected to the worm gear and then with reduction gear (gear ratio 80:1) and lastly with the help of nut and screw mechanism feed is given to the work piece. Tool rotating stepper motor is directly coupled with a hollow pipe whose another end is fixed with adjustable eccentric slide. Beneath this slide a wire vice is attached in which tool is fixed.

2.2 Electrolyte and Workpiece Material

- Throughout the experiments 20wt% NaOH solution[1] as electrolyte is used. It is so because most of the previous work has been done by NaOH and KOH solution which will help in comparing the results of the new method by the conventional drilling on non - conducting material by ECSM process.

  NaOH solution is first prepared and then allowed to cool down to room temperature. Dilution of the NaOH result in exothermic reaction. To minimize the evaporation losses from the electrolyte (or change in conductivity) it is kept in a closed vessel [9].

[1]On mass basis : by adding 20 g of NaOH flakes in 100 g of water

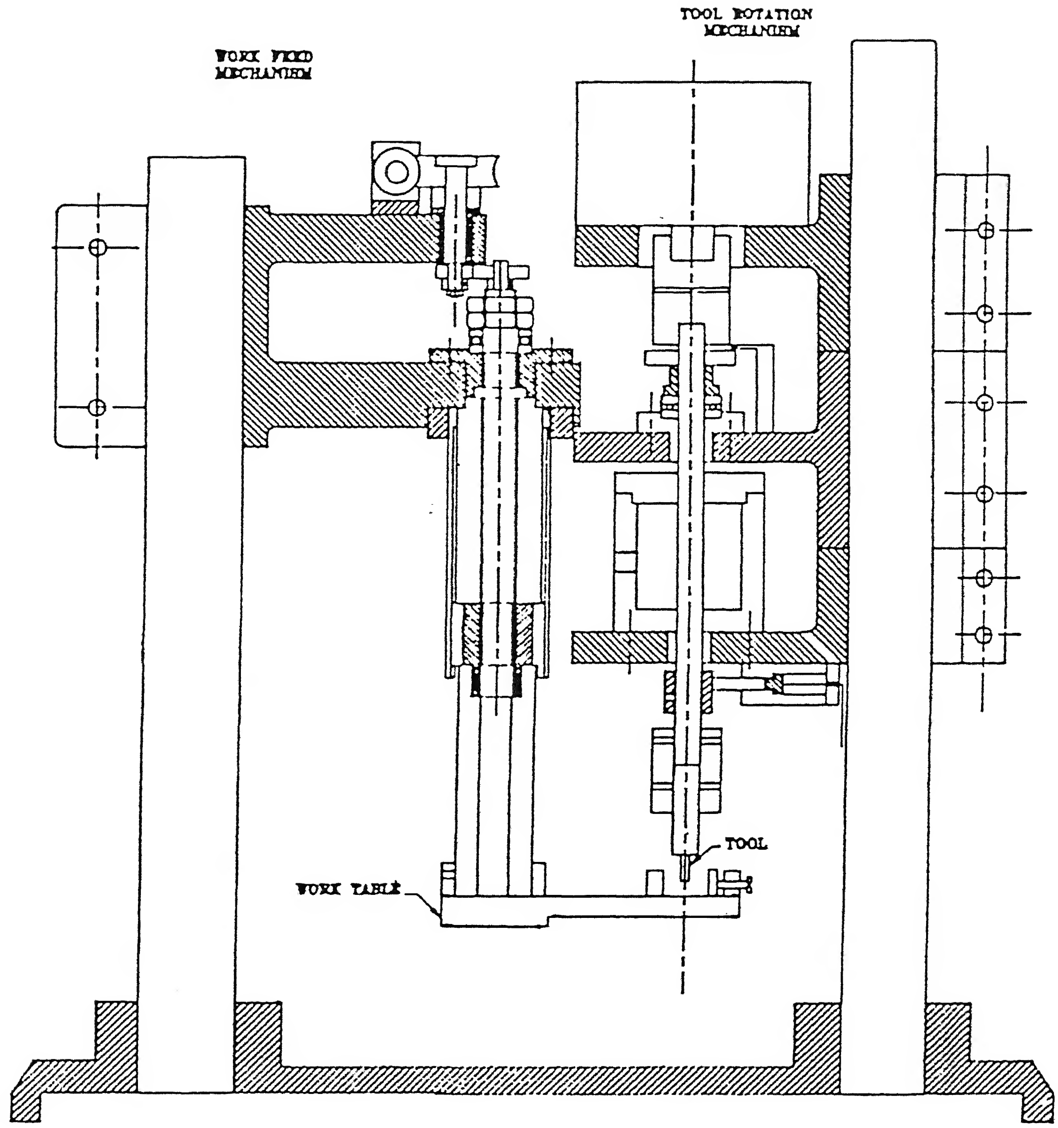
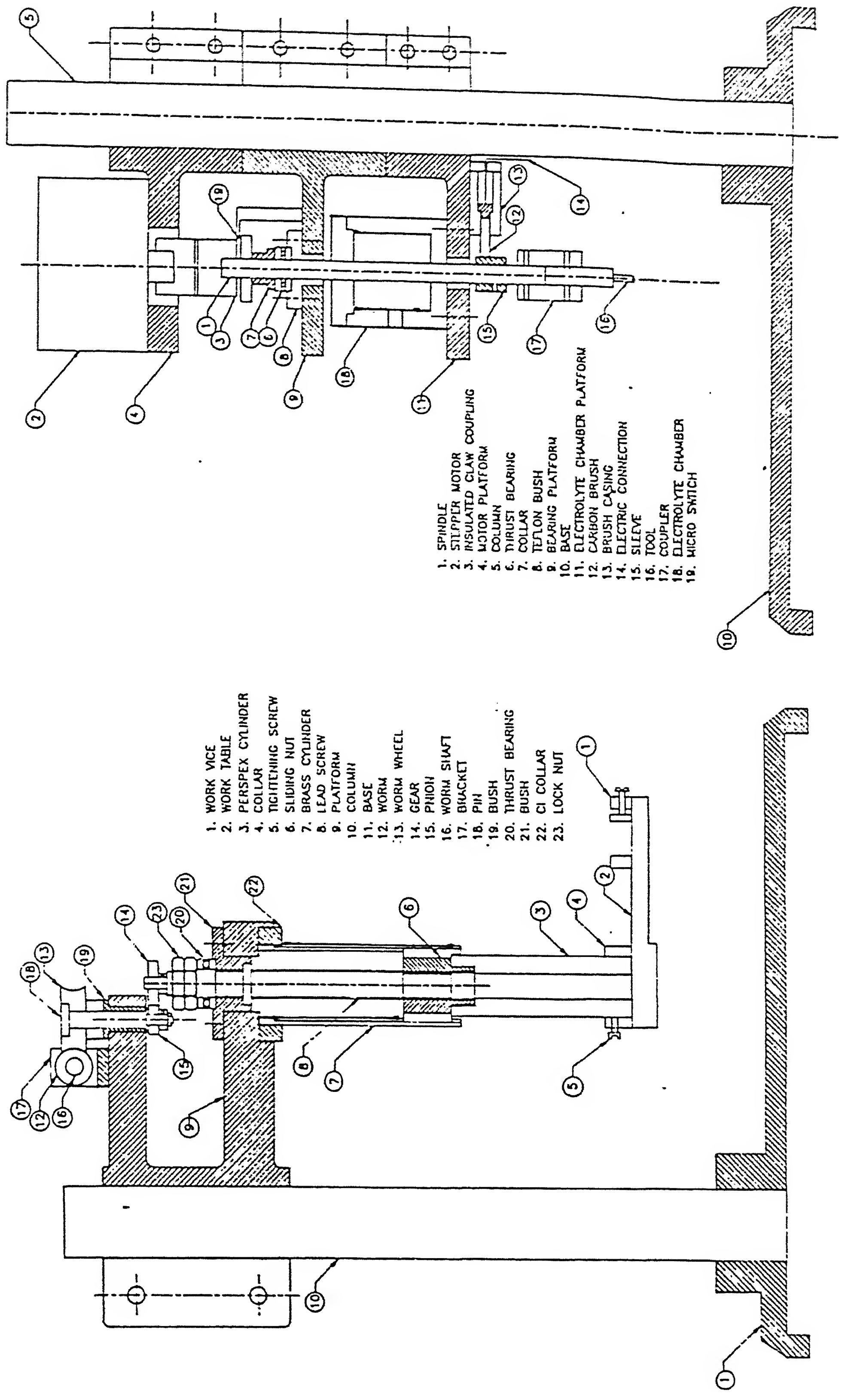


Figure 2.1: Electrochemical Spark Drilling Machine, [9]



(a) Workpiece holding mechanism.

(b) Tool holding mechanism.

Figure 2.2: Details Of Electrochemical Spark Machine, [9]

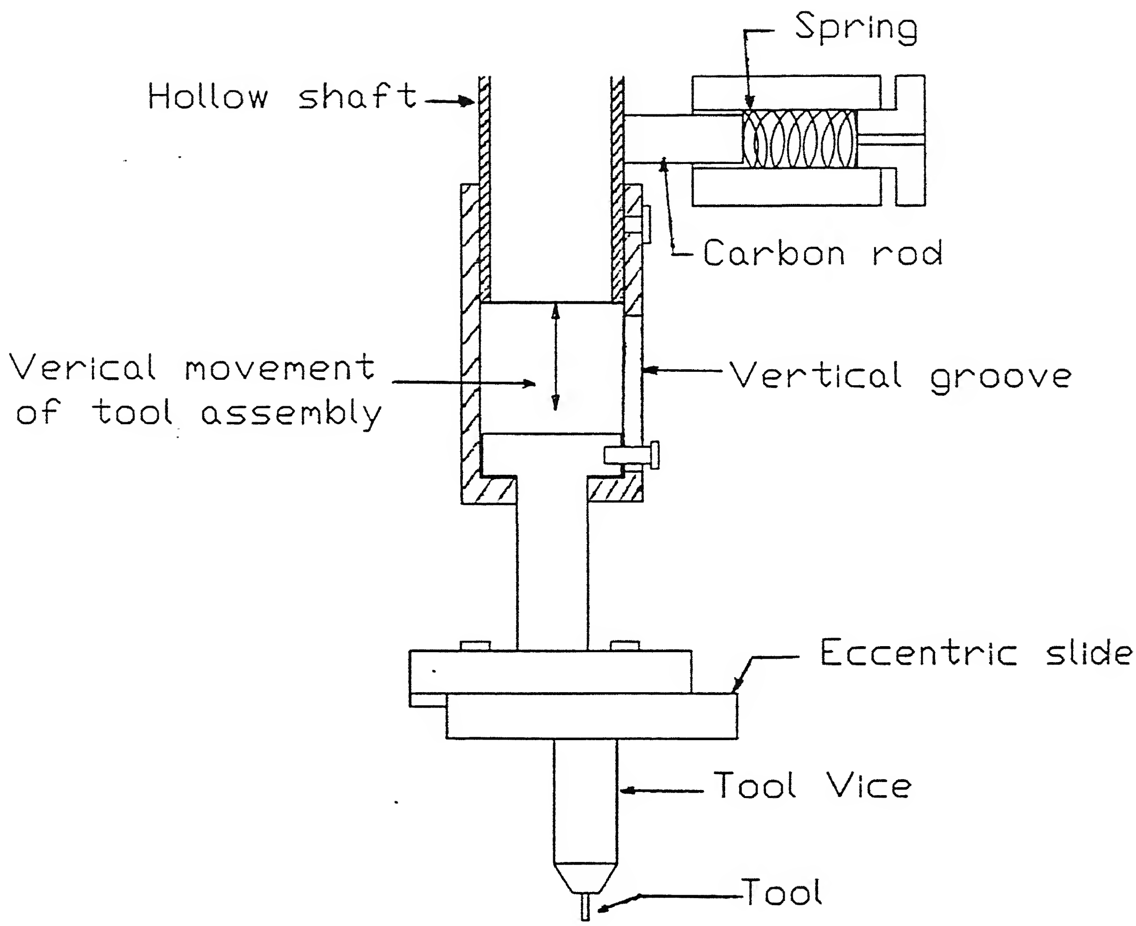


Figure 2.3: Eccentric Tool Design

Conductivity of the electrolyte is checked by the digital conductivity meter (Century make). It is calibrated by the standard known strength solution of potassium chloride (KCl). Throughout the experiments the conductivity of the solution is maintained almost constant.

- Work piece materials used are Alumina and Quartz which are non - conducting. Both the materials have high melting point, high hardness and brittleness.

  Quartz exhibits low thermal expansion, high resistance to thermal shocks, high chemical durability, high hardness, high transmission in the ultraviolet visible and infrared parts of the spectrum, and also possess following other properties:

  – Softening point = 1600^oC

  – Coefficient of thermal expansion = $0.627 * 10^{-6}K^{-1}$

  – Specific gravity at $20^oC = 2.21$

  – Thermal Conductivity = $1.382Wm^{-1}K^{-1}$

- Sintered Alumina is also one of the high temperature resistant material used for refractories, lamp tubes, grinding pebbles, polishing compounds, spark plugs, electronic substance, laboratory wares etc. It has some typical properties like:

  – Porosity upto 10% in Al_2O_3 can reduce the strength by 50%. Other mechanical properties are similarly affected.

  – The strength of alumina ceramic fall off substantially as the temperature increases beyond half of its melting point.

- Fracture in alumina occurs through the crystal as well as the boundaries. The nature of the fracture changes from transcrystalline to intercrystalline (grain boundaries) at the higher temperature, at which the strength decreases rapidly. The impurities in the specimens of purity better than 99%, probably concentrate at the grain boundaries.

- Alumina has poor resistance to thermal shocks; thermal stresses are particularly harmful during rapid cooling, in which the cooler exterior of the ceramic develops tensile stress resulting from differential volume changes.

  Since the compressive strength of the ceramic may be about eight times the tensile strength, consideration from the compressive stress point of view is not important. The theoretical consideration of the thermal shock behavior of brittle material is very complicated because of the fact that the properties of material vary with temperature. It is concluded that the stresses developed under the conditions of slow heating or cooling are also important

- Linear thermal expansion of Al_2O_3 ranges from $5.5 * 10^{-6}$ at $25°C$ to $10.0 * 10^{-6}$ at $1300°C$ [19]. Other properties of alumina are given in the appendix A.

• Copper wire of 1.24 mm diameter is used as a tool to perform treppaning operation on the workpiece material. The wire is held by a wire vice and about 5mm wire projects out of the vice. All the experiments are done by the same kind of wire. Tools coated with electrically non - conducting material (epoxy coating, ceramic coating) are also tried for machining but the coating could not resist high temperature, and easily got melted or detached from the tool.

2.3 Experimentation

The primary requirements for ECSM cell are two electrodes of different polarities and electrolyte. For the experimental work, tool (copper wire) is used as negative electrode and graphite rod is used as positive electrode. Experiments show reasonably good results when the electrolyte is heated. A copper wire of 1.24 mm diameter is used as tool kept in contact with workpiece by gravity feed. RPM of the tool at which it gives maximum machining is set for all the experiment i.e. 20 rpm [9]. Tool eccentricity is kept constant throughout the experiment.

NaOH 20wt% is used as electrolyte, and work pieces are cut by the help of diamond wheel in a shape which can easily be fastened on the work piece vice. Tool is fastened on the tool post (eccentric slide) especially manufactured for the adjustable eccentricity.

Electrolyte is heated at different temperature with the help of immersion heater to give the higher conductivity. Normally it is difficult to work at the temperature beyond 90^oC, because as the temperature increases the fumes concentration surrounding the workpiece increases to intolerable level. The tests were conducted at electrolyte temperature as $35^o, 50^o, 65^o$, and 80^oC which gives the conductivity of the NaOH electrolyte ranging from 345 mmho at (35^oC) to 650 mmho at (80^oC) for 20Wt%.

The conductivity range for each test is shown in the appendix B. The temperature of the electrolyte is kept fixed for each experiment with the help of thermostat control. It is always counter checked by thermometer.

The setup used for experimentation is shown on photograph (Fig 2.4) and the close view of the machined and unmachined workpiece surfaces are shown in Fig (2.5). Each test is conducted for 30 minutes and the level of electrolyte in the electrolyte tank is kept fixed by continuously supplying the electrolyte. We

tried to maintain the minimum amount of electrolyte over the workpiece so that contact between the tool and electrolyte should be kept minimum ie only at the tool tip, but the problem comes when the discharge zone shifts to upward direction. Because of downward movement of the tool towards the workpiece, it gives abrupt spark resulting high overcut on the machined surface.

The machined profile and the surface irregularities are traced on the paper with the help of shadow graph. The amount of material removed is measured by the 'weight loss'. The workpiece weight is measured before machining and after machining. Before weighing each time, it is thoroughly washed and dried. The loss of weight shows the material removed during the period of test. Weight is measured on the digital weighing machine having the accuracy of .0001 gm.

Machine depth on the workpiece is measured by a dial gauge, whose accuracy is .01 mm and the diameter of the plunger tip is .025 mm. Description of the dial gauge is given in chapter 3.

Study of the machined profile is done by SEM (Scanning Electron Microscope) and the circularity error with taper angle on vertical face is done by Shadowgraph. The format of constant test conditions during the experiment is shown at table 2.1.

Table 2.1: Constant test conditions during the experimentation

Voltage range = 50 - 70	Workpiece mats. = Alumina, Quartz
Tool mat. = copper	Tool eccentricity = 3.0 mm
Tool rpm = 20	Tool dia. = 1.24 mm
Conductivity of the electrolyte at room temperature (25°C) = 310 mmho	Time duration = 30 min.

Figure 2.4: Photographs of the experimental set-up

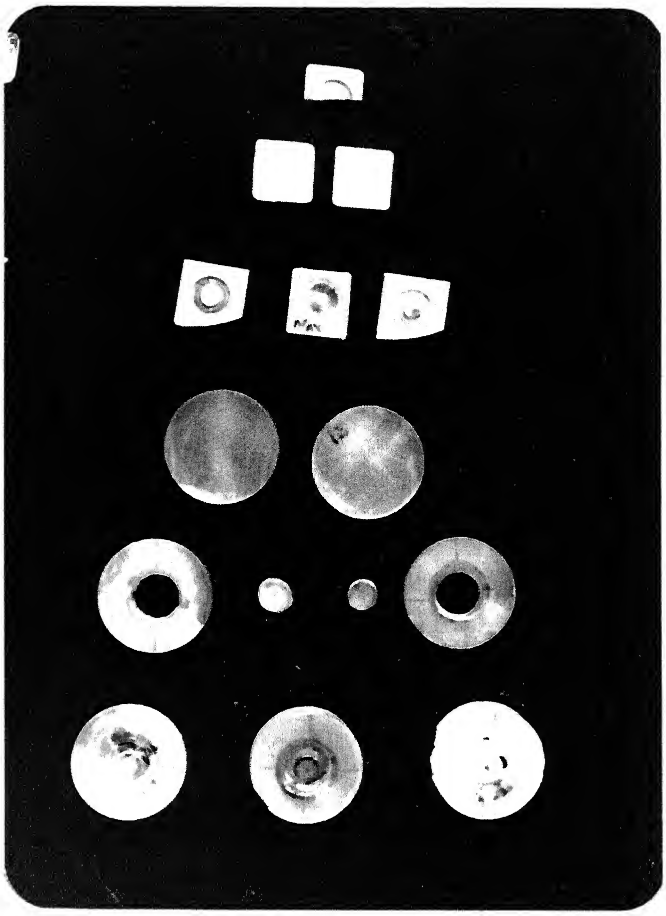


Figure 2.5: Close view of machined and unmachined samples

Chapter 3

Results and Discussion

This chapter deals with experimental observations related to ECSM process, where the effects of process parameters and the resulting machined profile are studied. Some work has already been done in the past in the similar area. However, The work reported in this thesis is different from the work done by earlier researchers, from the following view points :

- The work material used are Alumina and Quartz which have been machined using eccentrically rotating tool. The tool is given gravity feed to make sure that it touches the workpiece. Earlier work [9] was conducted with an appropriate gap between the tool and workpiece.

- To increase the conductivity of the NaOH electrolyte (maximum is at 22.5% by weight concentration), the temperature of the electrolyte was increased in the steps of 15°C, starting form 35°C to 80°C. Various input voltages used were 50V, 60V, and 70V. Earlier work [9] has used electrolyte at room temperature.

- Efforts were also made to evaluate, if the use of an inductor could help in drilling cavity / hole in the workpiece.

  Experiments have been conducted on two kind of work materials viz Alumina and Quartz. During experimentation, the variables used were electrolyte

temperature and input voltage. The detailed observations made in each case, are reported below.

3.1 Machining Of Alumina

3.1.1 Effect Of Electrolyte Temperature

The effects of electrolyte temperature on the following responses have been studied :

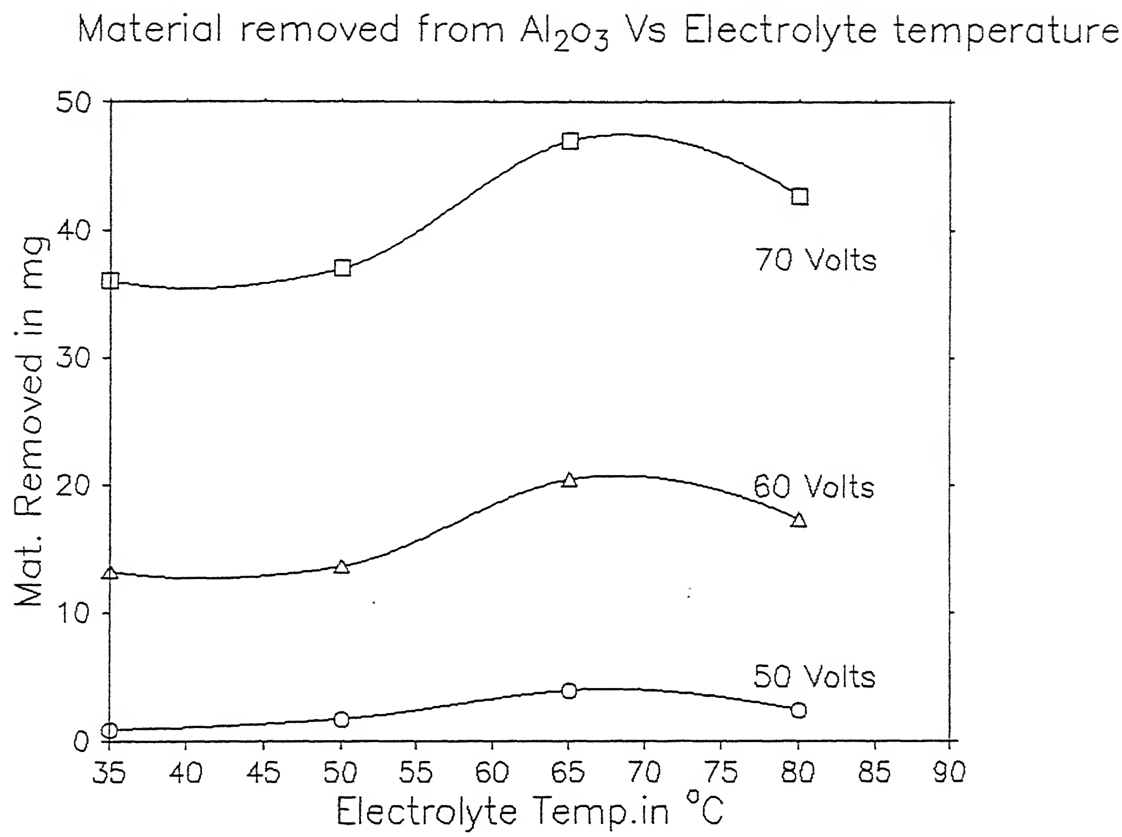
1. Material removed from the workpiece,
2. Machined depth achieved in the workpiece, and
3. Overcut obtained on the machined profile.

The machining conditions that were kept unchanged during various experiments are given in the table in Fig. 3.1.

Material removed from the workpiece

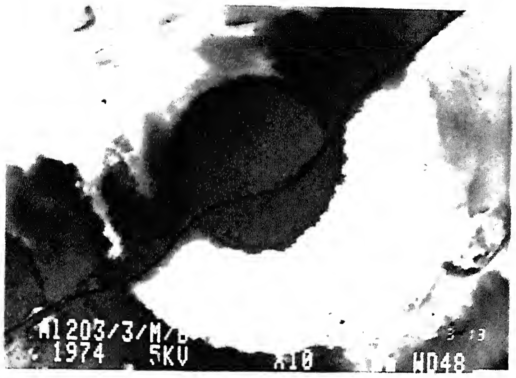
Material removed from the workpiece is measured in terms of loss of weight as explained in chapter 2. It is observed during the experiments that almost in every case the material removed from the workpiece increases with electrolyte temperature upto 65°C, and after that it starts decreasing (Fig. 3.1).

Maximum material removed is achieved at 65°C electrolyte temperature and 70 volt as input voltage. Therefore, the test for through hole trepanning is conducted at 65°C and 70volts. Unfortunately, we couldn't get success in making a through hole in Alumina. However, we achieved the maximum material removed ie. 122.7 mg (with the tool of 1.24 mm diameter, 20 rpm speed, eccentricity = 3.0 mm, and machining time = 1 hour, 10min.). Beyond this combination of conditions, machining could not be done because the workpiece material showed strong susceptibility towards cracking.



"workpiece material = (Al_2o_3)"	conductivity at 35°c = 350 – 355 mmho
"tool dia = 1.24mm"	50°c = 463 – 470 mmho
"tool material = copper"	65°c = 543 – 552 mmho
"tool rpm = 20"	80°c = 630 – 650 mmho
"tool eccentricity = 3.0 mm"	concentration 20wt% NaOH
"machining time = 30 min."	

Figure 3.1: Constant machining conditions during experiments



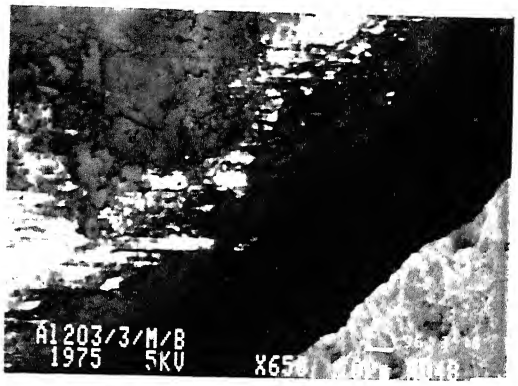


Figure 3.2: Full view of machined surface having through crack, Sample no: (3)

Fig. 3.2 shows the photograph of a cracked workpiece obtained while machining at the above stated machining conditions.

Machined depth on the workpiece

Machined depth on the workpiece is measured with the help of a dial gauge set - up shown in Fig 3.3. Dial gauge is rigidly fixed on a vertical bar whose one end is fixed with the surface - plate. Workpiece is kept on the surface - plate for the measurement of machined depth. The relative vertical displacement of plunger between the unmachined and machined surface shows the depth achieved on the workpiece by ECSM process. The accuracy of the dial gauge is .01 mm and the radius of the plunger tip which touches the machined surfaces is 0.125 mm.

The nature of curves showing the effect of electrolyte temperature on machined depth achieved in workpiece material is the same as that obtained for material removed, Fig 3.1. The maximum depth is achieved at 65°C and 70 volt. The results obtained are shown in Fig.3.6. However, we obtained the maximum machined depth i.e. 1.35 mm (with the tool of 1.24 mm diameter, 20 rpm speed, eccentricity

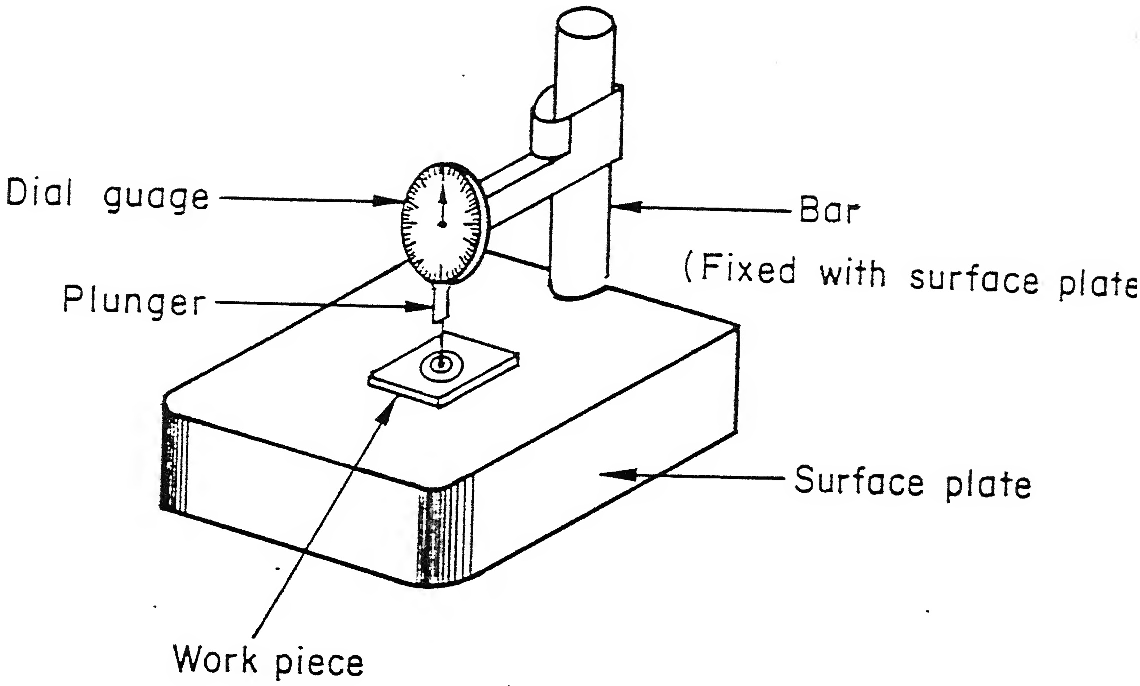


Figure 3.3: Setup for machine depth measurement

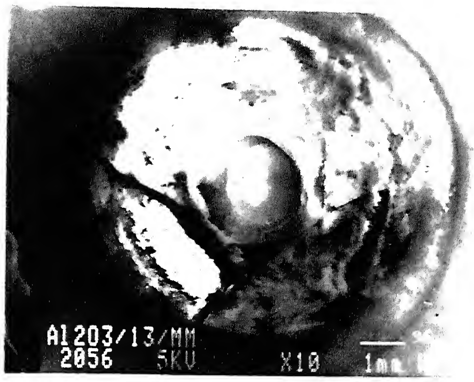


Figure 3.4: Full view of the max. machined surface tried for through hole. Sample: (13)

= 3.0 mm. and machining time = 1 hour, 10 min. Fig. 3.4).

Overcut on the machined profile

Overcut on the machined profile is measured using a shadowgraph. The magnified images (X 10) of machined profiles (shadowgraphs) are analyzed and the results are given in Fig 3.7. Overcut is measured by subtracting the tool diameter (d) from the width (W) of the machined profile. Width of the machined profile and the dia. of the tool are measured with the help of micrometer attached to the shadowgraph whose accuracy is .001 mm.

Diameteral Overcut (O_d) is given as :

$$O_d = W - d$$

3.1.2 Effect Of Supply Voltage

The effects of supply voltage on the following responses have been studied while ECSM of Alumina :

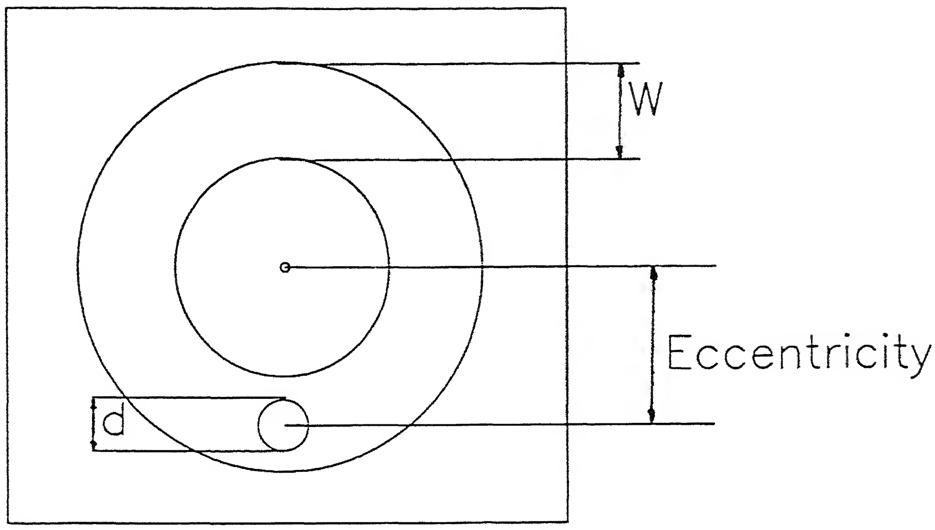


Figure 3.5: Schematic diagram for Overcut on the machined profile

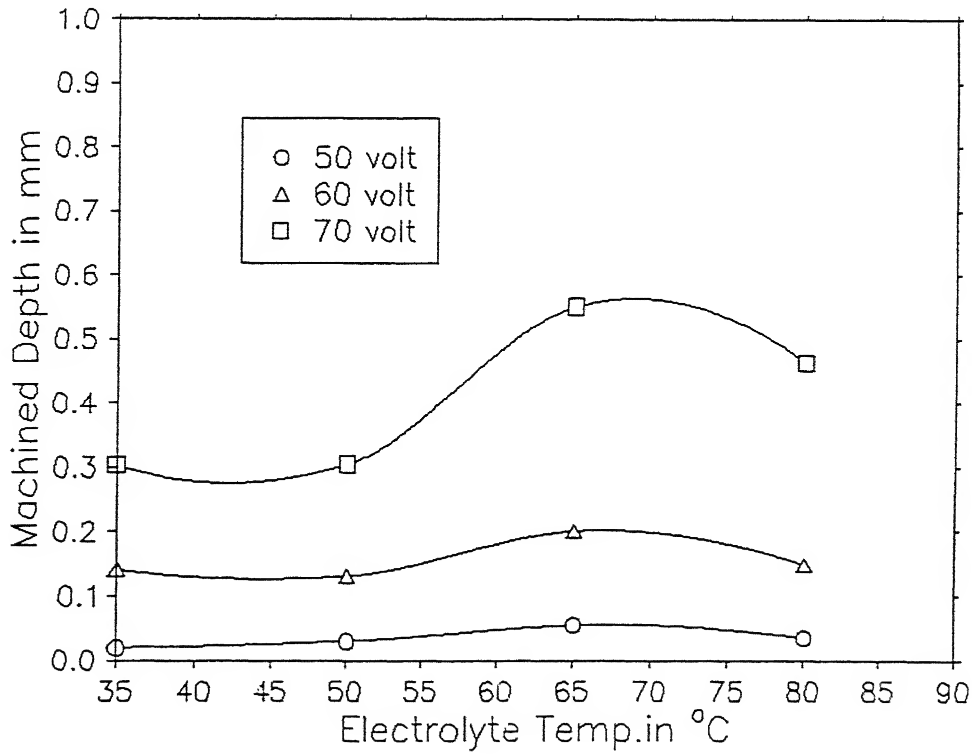


Figure 3.6: Machined depth achieved in Al_2O_3 Vs Electrolyte temperature

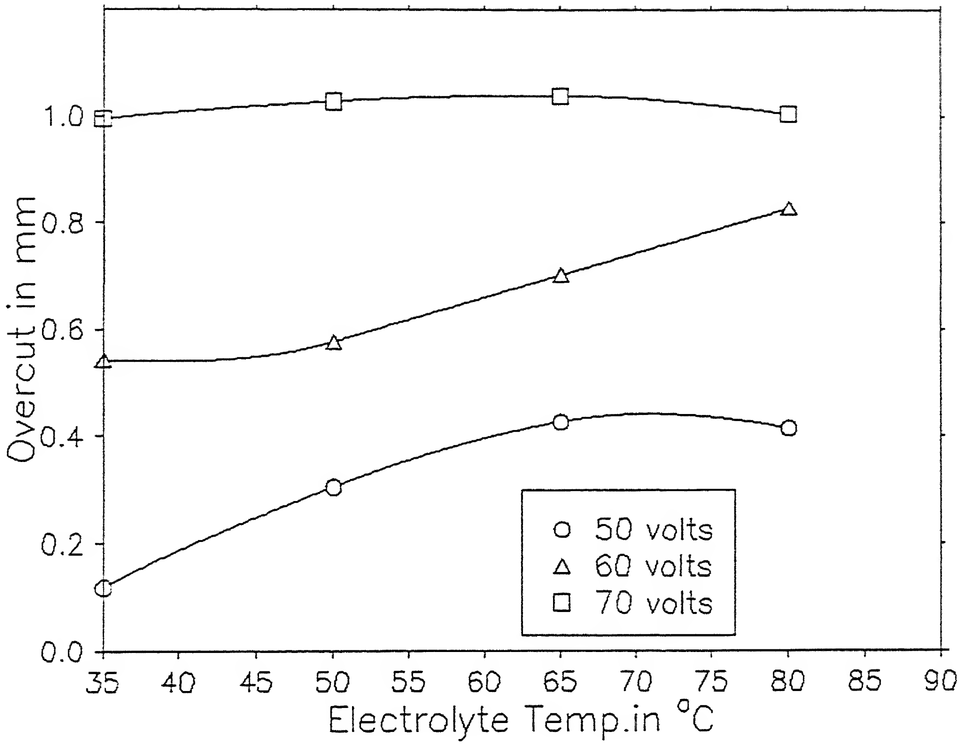


Figure 3.7: Overcut in Al_2O_3 Vs Electrolyte temperature

1. Material removed from the workpiece,
2. Machine depth achieved in the workpiece, and
3. Overcut on the machined profile.

Material removed from the workpiece

The effect of supply voltage on the material removed from the workpiece indicates that as the supply voltage increases, the material removed from the workpiece also increases. But the maximum material is removed at 65°C and 70 volts. Results are shown in Fig. 3.8.

Machined depth on the workpiece

Similar results are obtained for the machined depth achieved on the workpiece material for the same range of voltage. Machined depth increases with supply

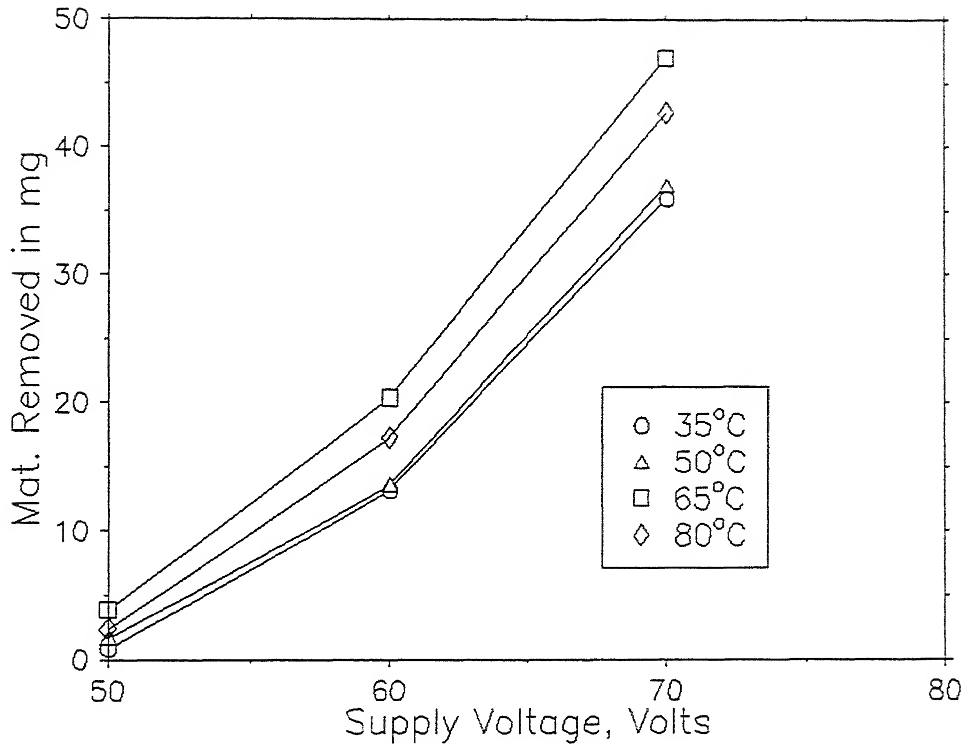


Figure 3.8: Material removed from Al_2O_3 Vs Supply Voltage

voltage and the maxima is attained at 65°C and 70 volts, Fig 3.9.

The reason for this kind of behavior is that as the supply voltage increases, the intensity of current drawn from the tool increases, which increases the electrical as well as thermal shocks including the heat generated at the vicinity of the tool and workpiece contact point. Therefore the erosion of material from the workpiece increases with increase in current Intensity.

Overcut on the machined profile

Study of overcut by the shadowgraph shows that with the increase in supply voltage the overcut increases, Fig. 3.10.

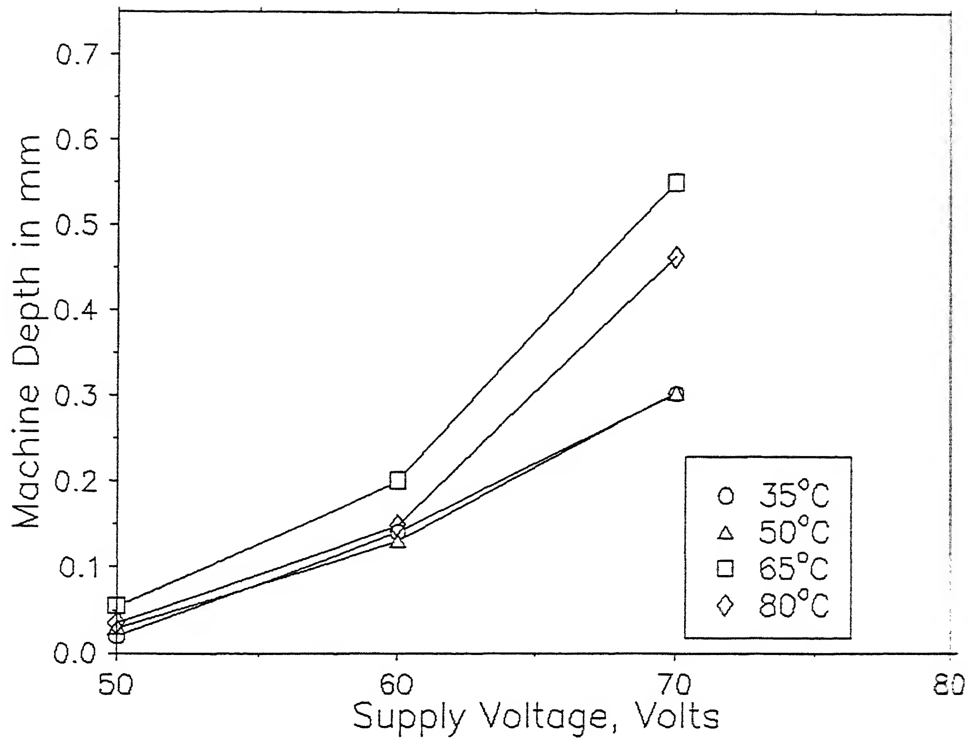


Figure 3.9: Machined depth achieved in Al_2O_3 Vs Supply Voltage

3.2 Machining Of Quartz

As seen in the following discussion, qualitatively the effect of ECS machining parameters like electrolyte temp. and supply voltage on the responses (MRR, MD, O_d) during trepanning operation on Quartz are almost the same as in case of Alumina.

3.2.1 Effect Of Electrolyte Temperature

The effects of electrolyte temperature on the following responses have been studied :

1. Material Removed from the workpiece,
2. Machine depth achieved in the workpiece, and
3. Overcut on the machined profile.

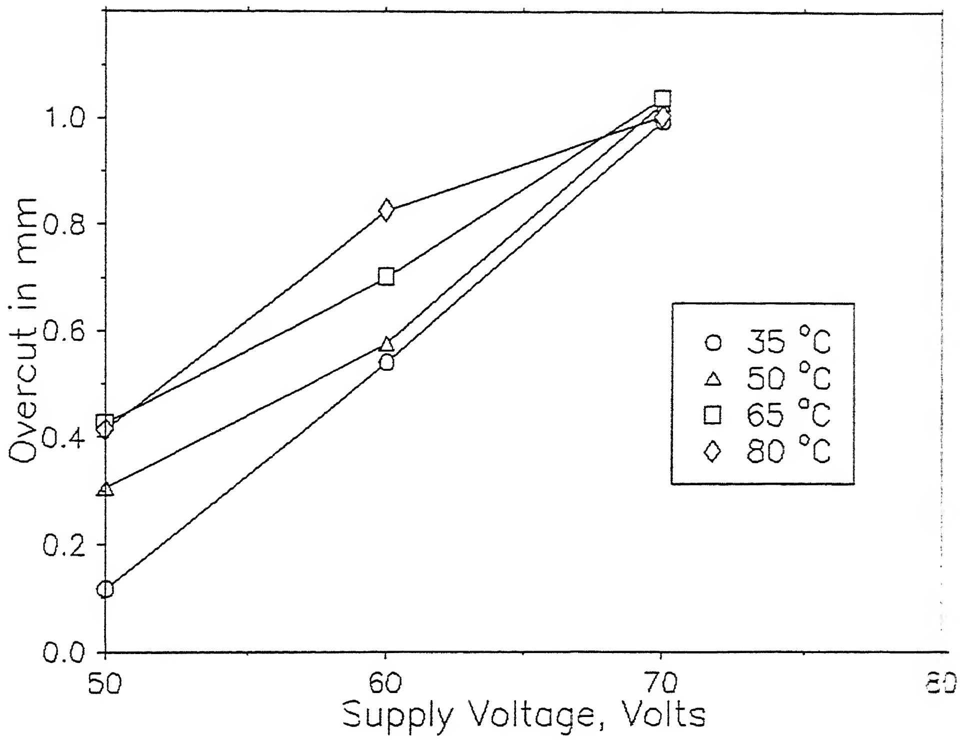


Figure 3.10: Overcut on machined profile in Al_2O_3 Vs Supply Voltage

Material removed from the workpiece

The effect of electrolyte temperature on the material removed from Quartz shows that with the increase in electrolyte temperature the material removal increases, and after 65°C it starts decreasing (Fig. 3.11). It follows the same trend as in the case of Alumina, Fig. 3.1.

Machined depth on the workpiece

The results related to machined depth obtained while machining Quartz are shown in Fig. 3.12. The maximum machined depth is achieved at 65°C and 70 volts as in the case of Alumina.

In the case of Quartz we have been able to make a through hole in the sample of thickness is 2.35 mm only in 14 min. Fig. 3.25 (a) shows the specimen with the through hole and the table shown in the Fig. 3.10 gives the machining conditions at

which this test was conducted. The maximum material removed and the machined depth achieved in a test of 30 min. are 576.7 mg and 4.21 mm, respectively. Why the machining condition is much favorable at 65°C and 70 volts ? The definite reasoning for this particular behavior could not be found.

Overcut on the machined profile

The effect of electrolyte temperature on the overcut shows that the overcut decreases after a certain value of electrolyte temp. while the overcut increases with an increase in supply voltage, Fig. 3.13.

Accurate measurement of the overcut was found to be difficult because the transparency of the workpiece made it difficult to focus accurately. Hence, the trend at different voltages seems to be different.

3.2.2 Effect Of Supply Voltage

While machining Quartz the effects of supply voltage on the following responses have been studied.

1. Material removed from the workpiece,
2. Machine depth achieved in the workpiece, and
3. Overcut on the machined profile.

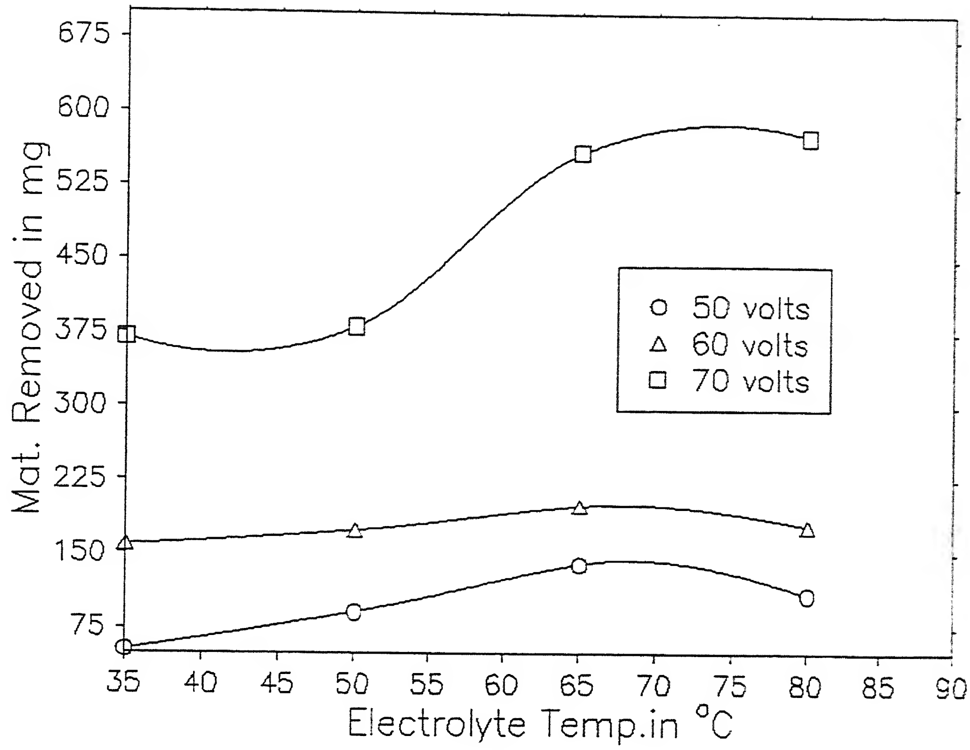


Figure 3.11: Material removed from Quartz Vs Electrolyte temperature

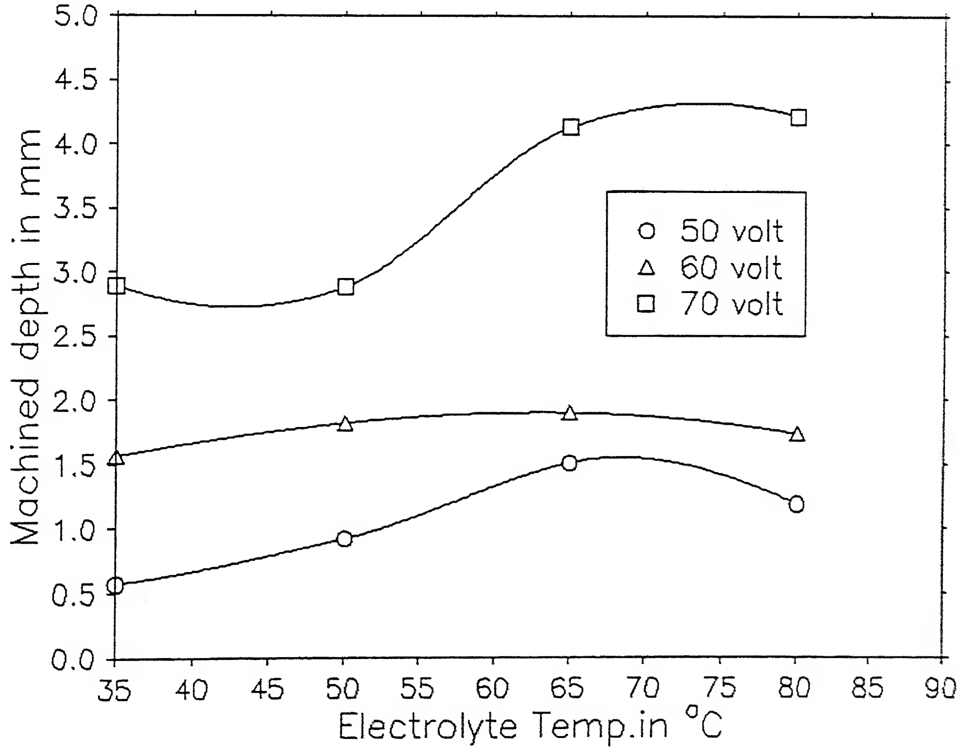


Figure 3.12: Machined depth achieved in Quartz Vs Electrolyte temperature

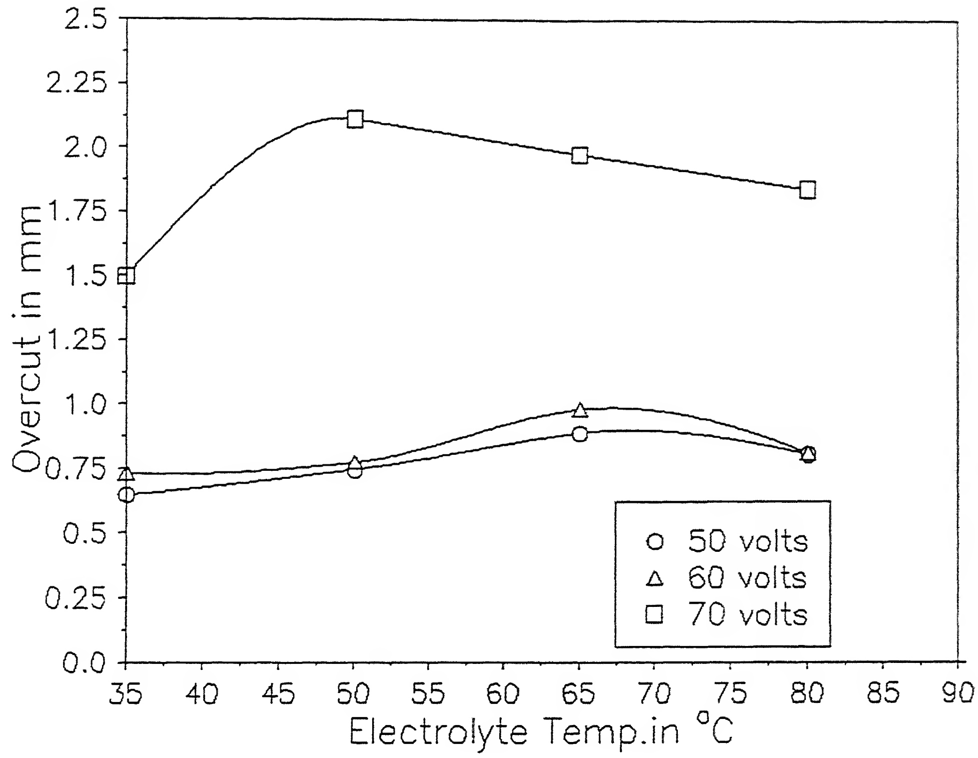


Figure 3.13: Overcut in Quartz Vs Electrolyte temperature

Material removed from the workpiece

Fig. 3.14 shows the effect of supply voltage on material removed from the workpiece. Material removed increases with increase in supply voltage. Further, it is also observed that the increase in material removal in the range of 60 - 70 volts is significant in comparison to 50 - 60 volts range.

Machined depth and Overcut on the machined profile

Similar trend is exhibited in case of the effect of supply voltage on machined depth (Fig. 3.15) and overcut obtained (Fig. 3.16). The values of machined depth and overcut obtained in case of Quartz are higher in the range of 60 - 70 volts in comparison to 50 - 60 volts.

Fig. 3.17 - 3.22 shows a comparison of values obtained for Alumina and Quartz.

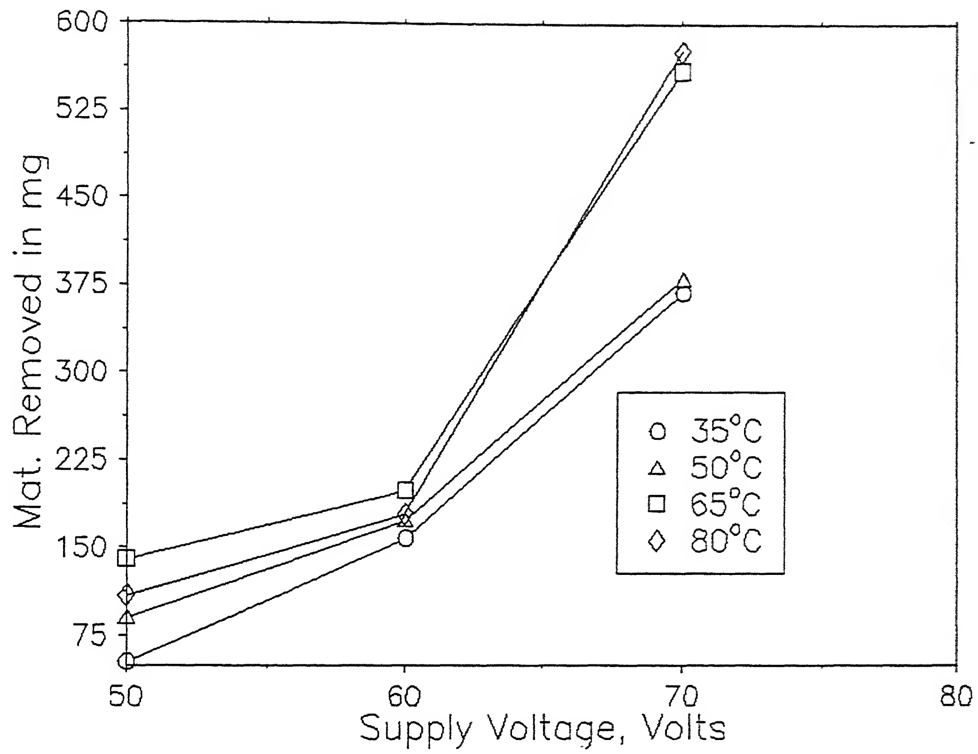


Figure 3.14: Material removed from Quartz Vs Supply Voltage

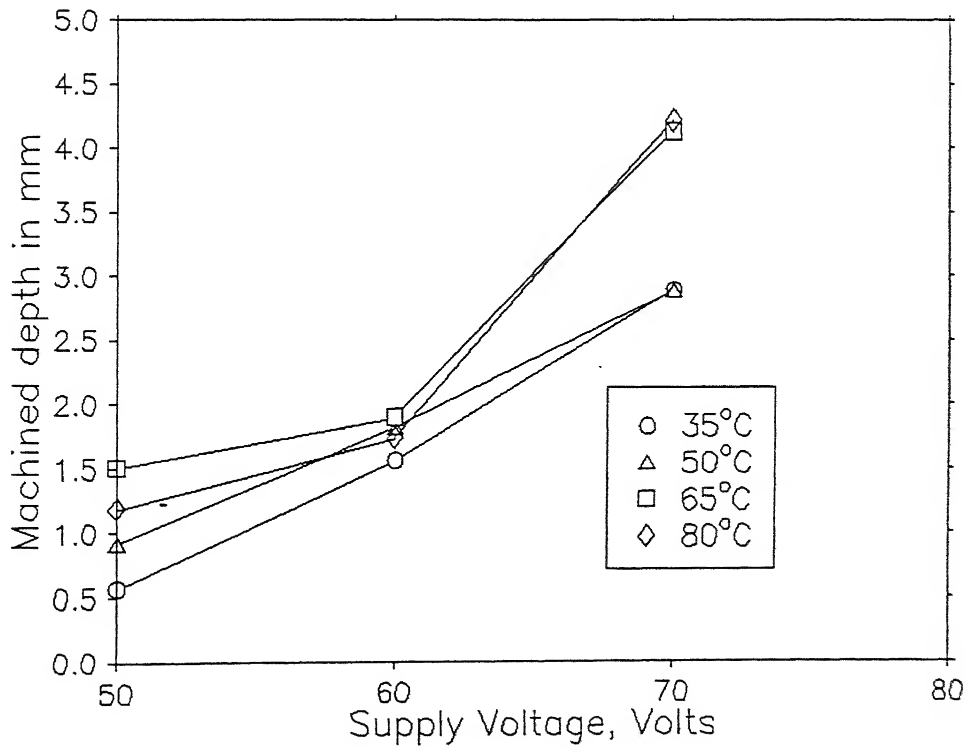


Figure 3.15: Machined depth achieved in Quartz Vs Supply Voltage

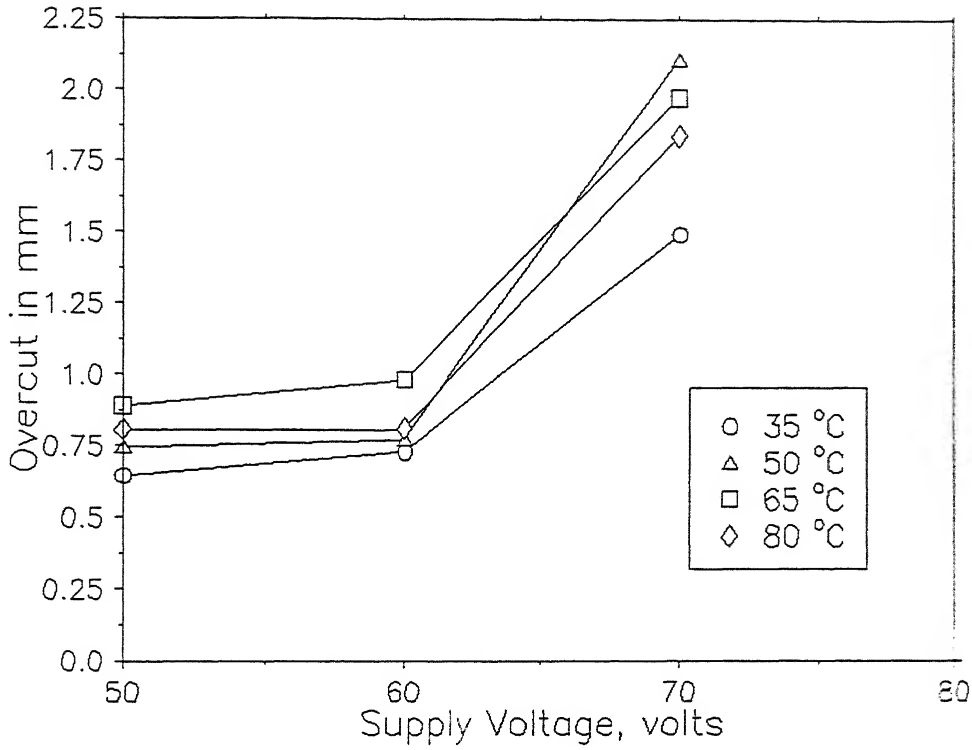


Figure 3.16: Overcut in Quartz Vs Supply Voltage

3.3 Study Of Machined Profile

Taper angle of electrochemical spark trepanned hole in Al_2O_3 and Quartz is studied by shadowgraph shown in Fig 3.23 (a). Maximum taper angle is observed when the tool is fed by gravity and kept stationary. However, the use of off the center rotating tool reduces the circularity error [9]. The machined profile achieved by ECS trepanning method for the case of max. material removed in Alumina is shown in Fig (3.23 (b), (c), &(d)).

In the case of alumina, overcut on the machined profile is low and taper angle is high. It is so because, thermal conductivity of alumina is low therefore there is no proper distribution of heat over the workpiece material. Upper layer of alumina gets high heat from the spark, while the bottom surface gets low amount of heat. Therefore, the erosion of material from the upper portion is higher in comparison to lower portion. But in the case of quartz, it has higher thermal conductivity.

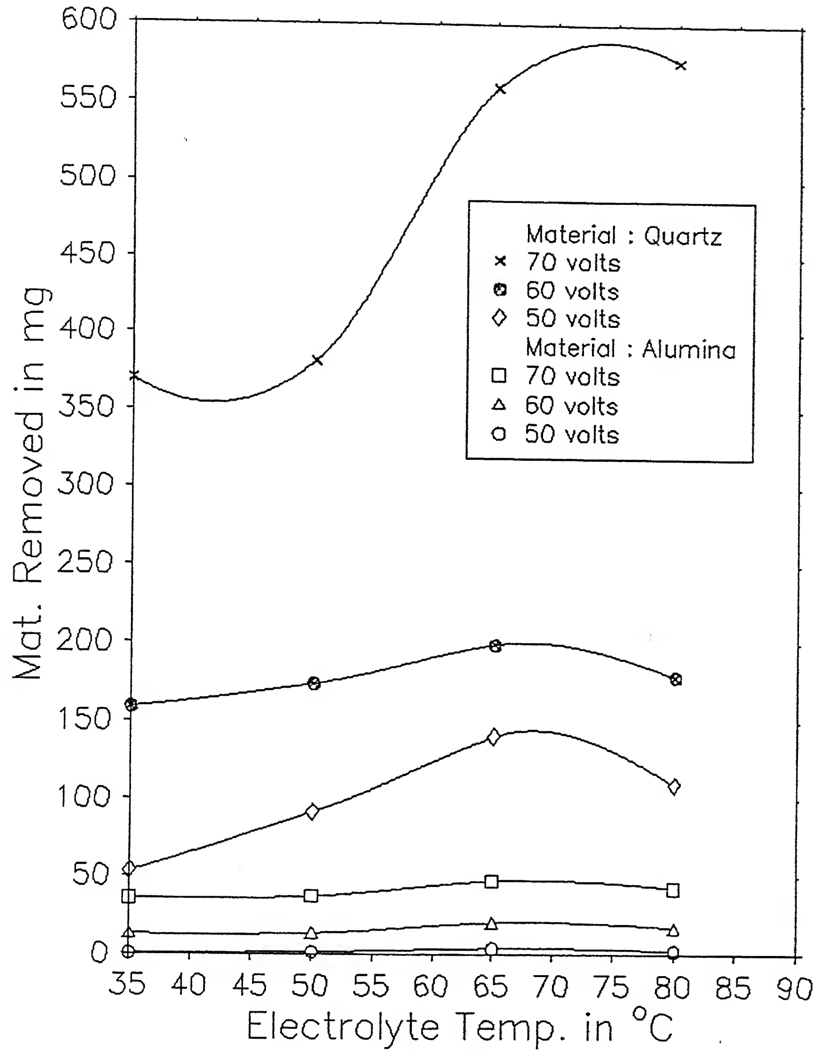


Figure 3.17: Material removed from Quartz and Al_2O_3 Vs Electrolyte temp.

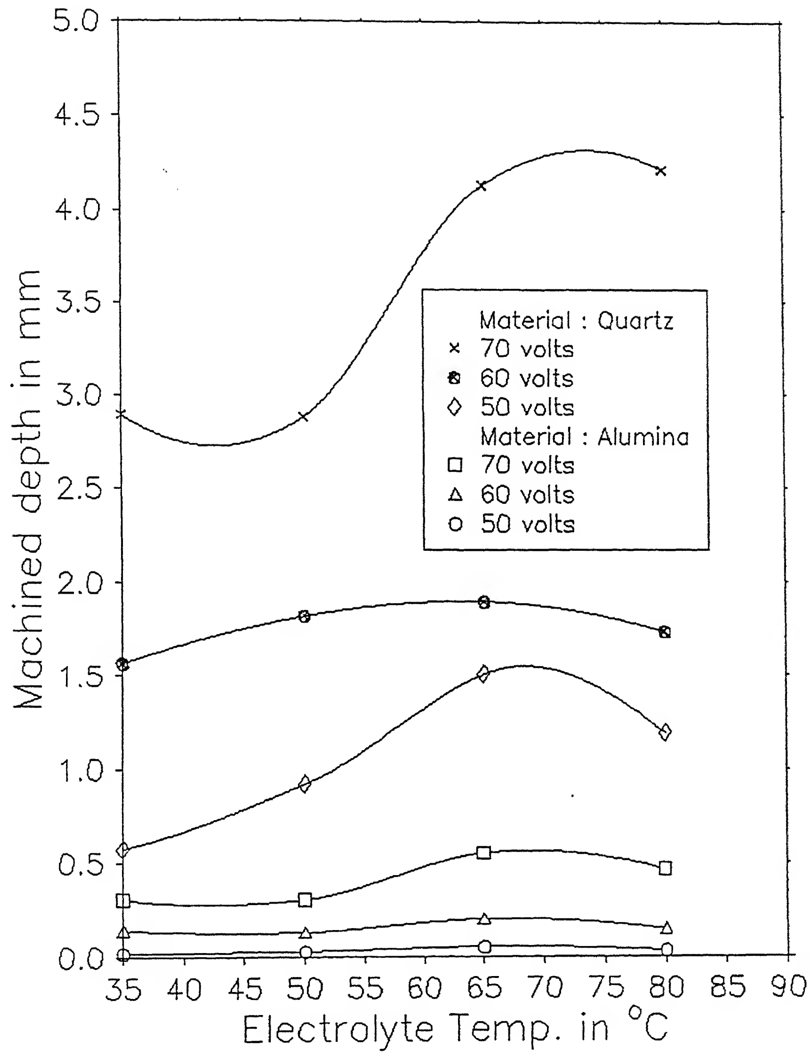


Figure 3.18: Machined depth achieved in Quartz and Al_2O_3 Vs Electrolyte temp.

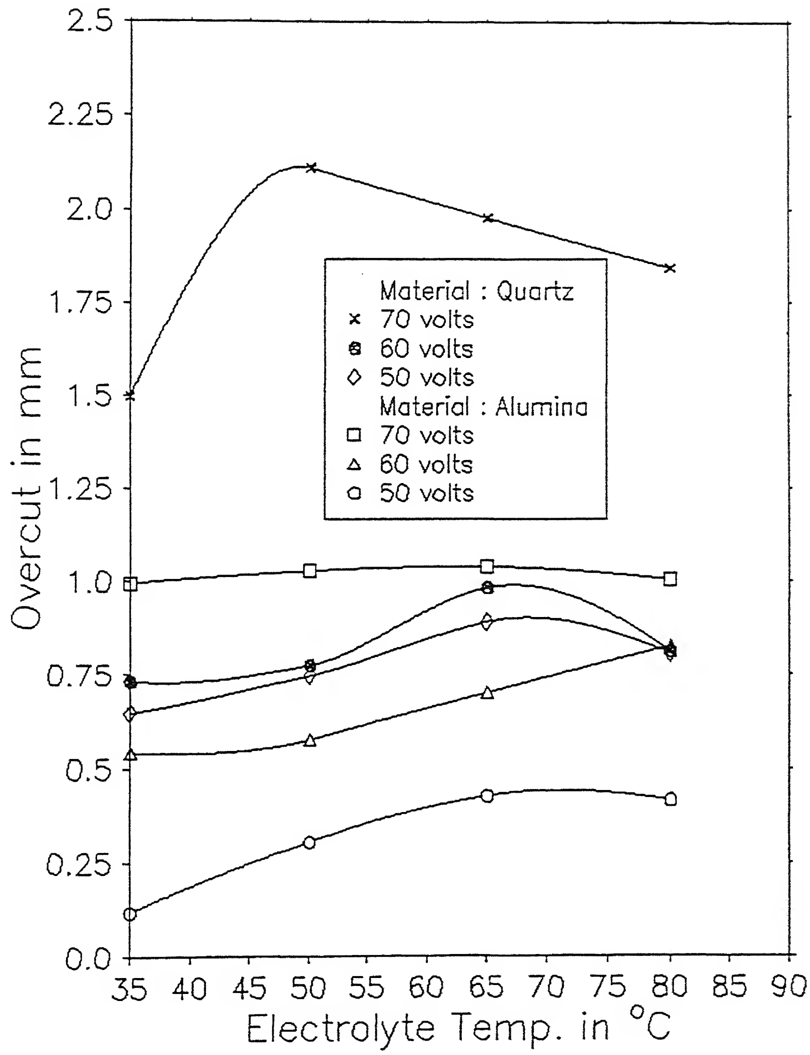


Figure 3.19: Overcut in Quartz and Al_2O_3 Vs Electrolyte temp.

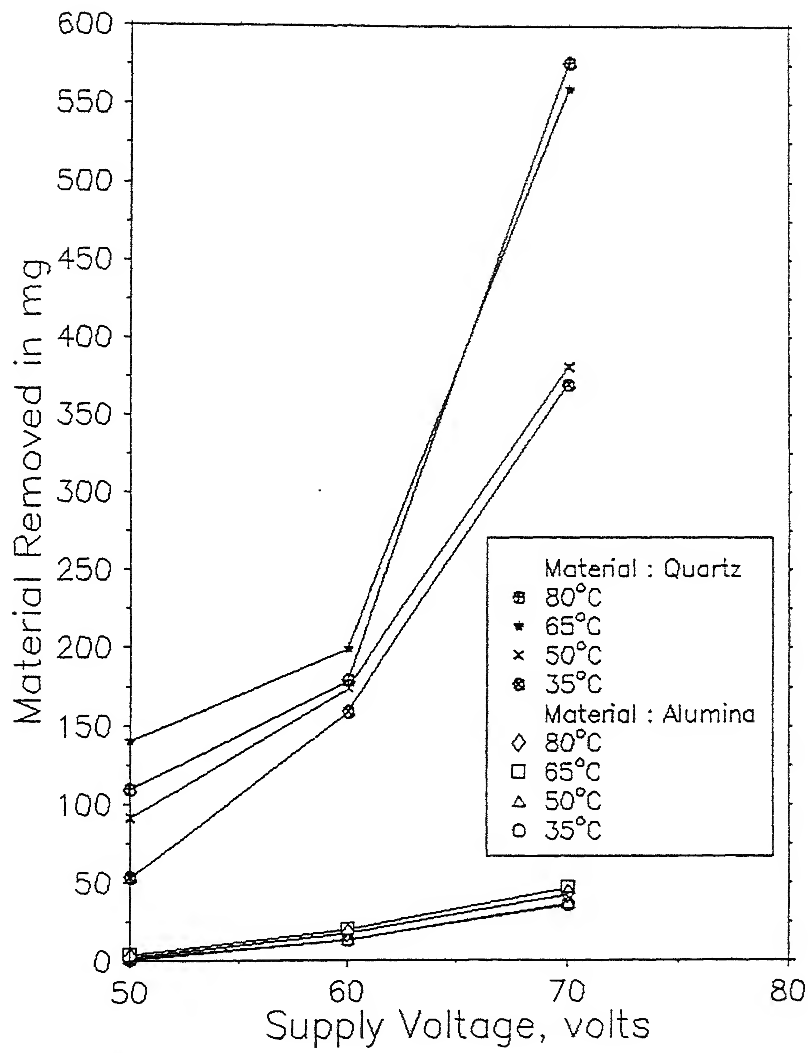


Figure 3.20: Material removed From Quartz and Al_2O_3 Vs Supply Voltage

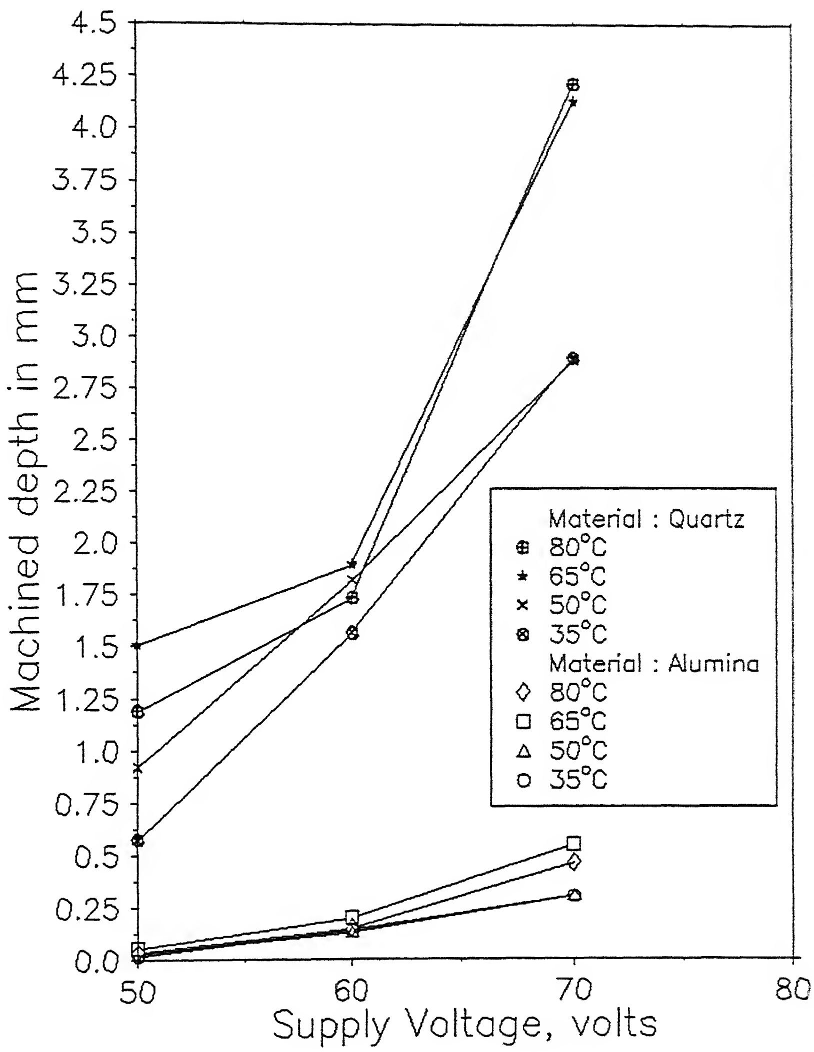


Figure 3.21: Machined depth achieved in Quartz and Al_2O_3 Vs Supply Voltage

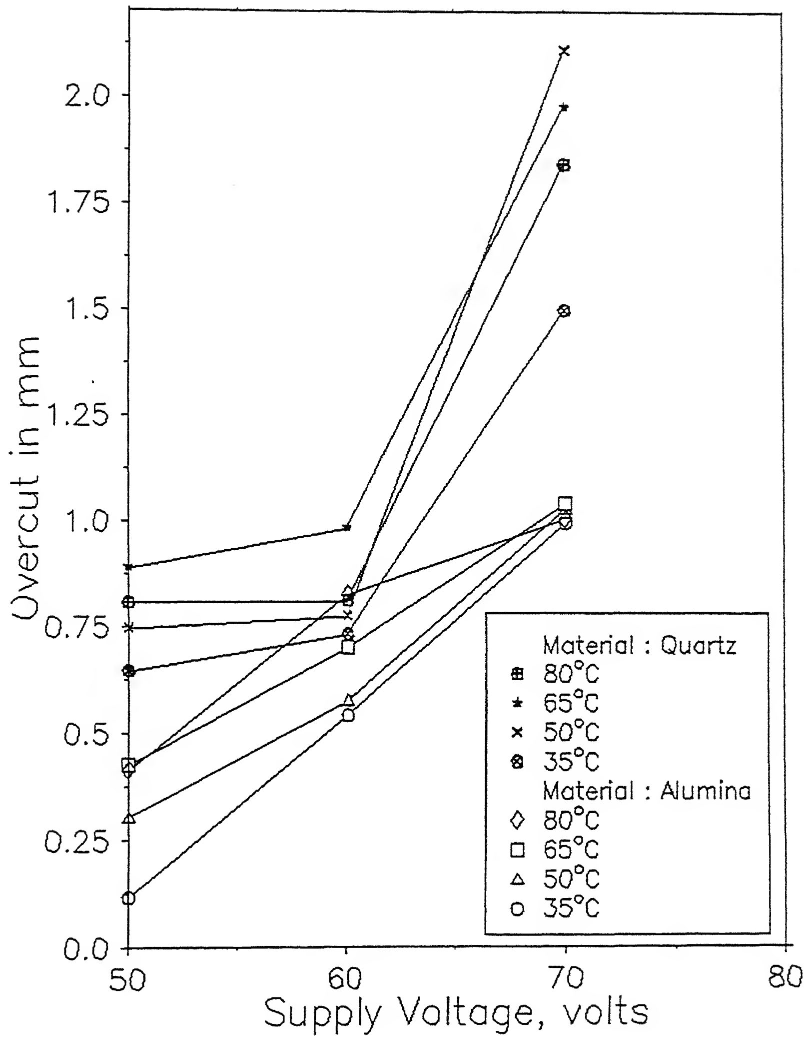


Figure 3.22: Overcut in Quartz and Al_2O_3 Vs Supply Voltage

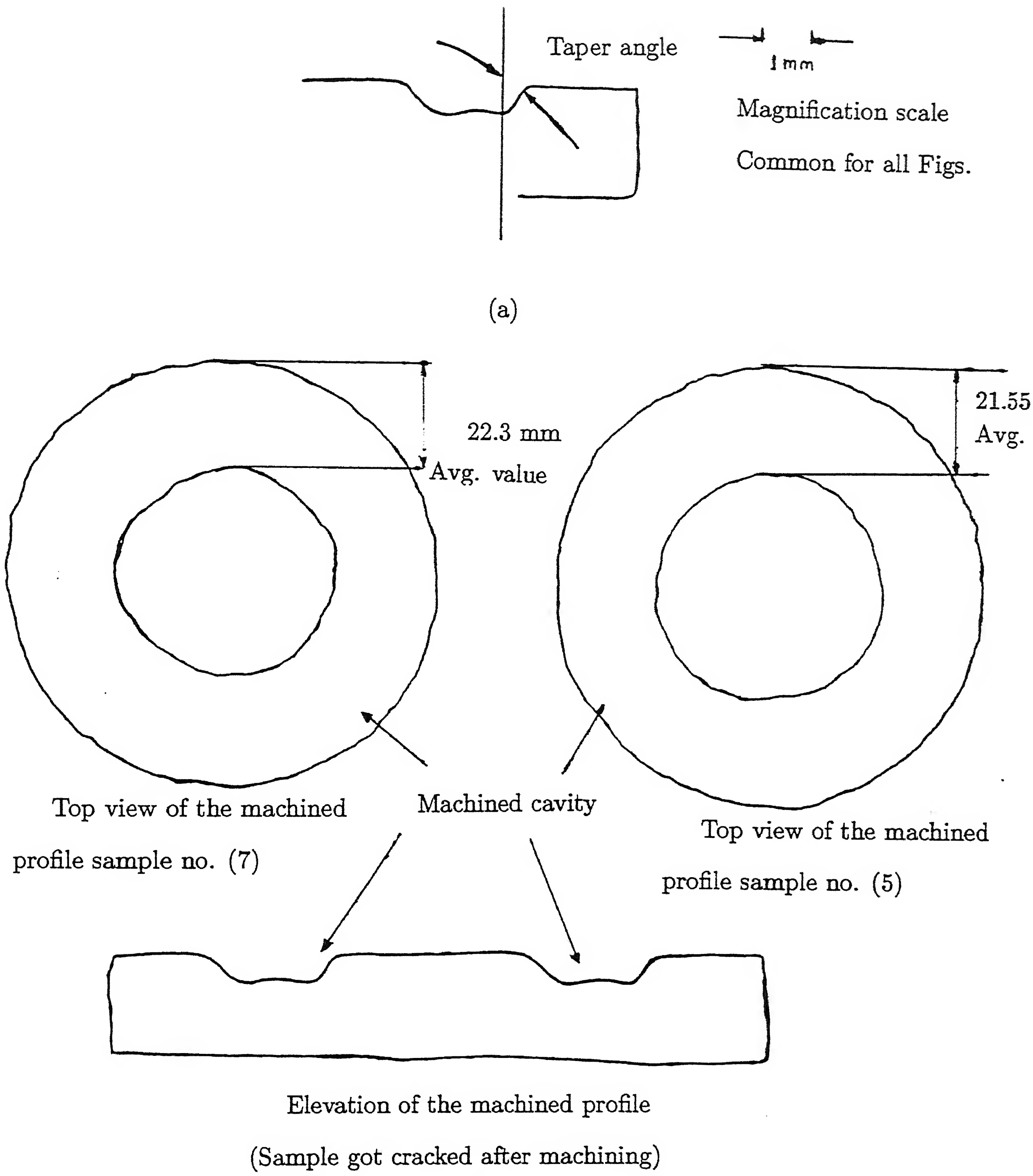
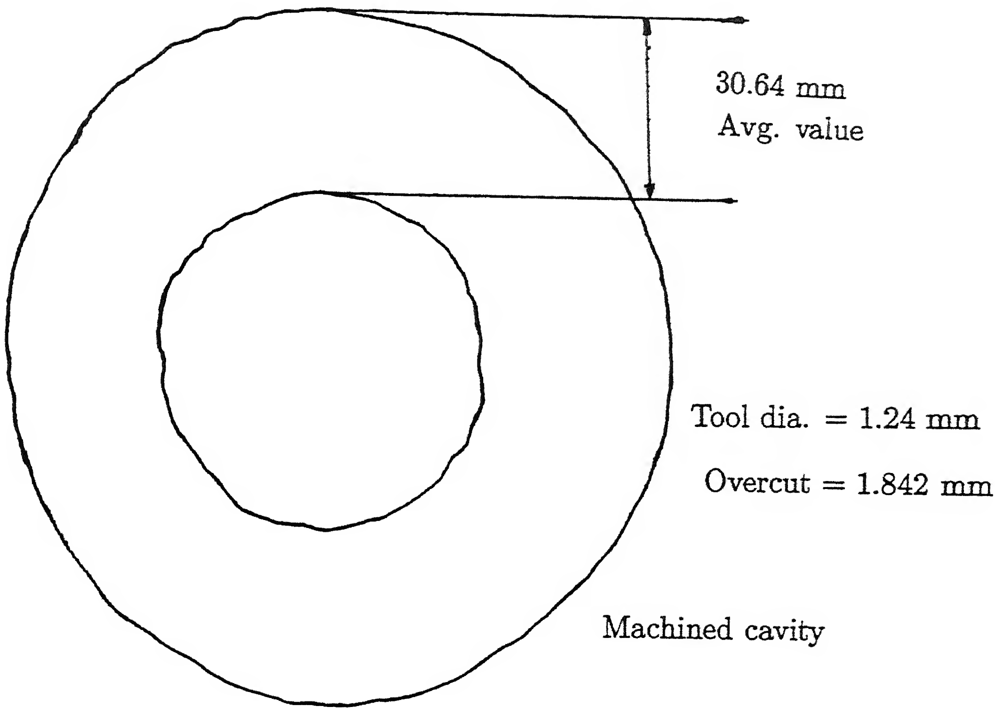
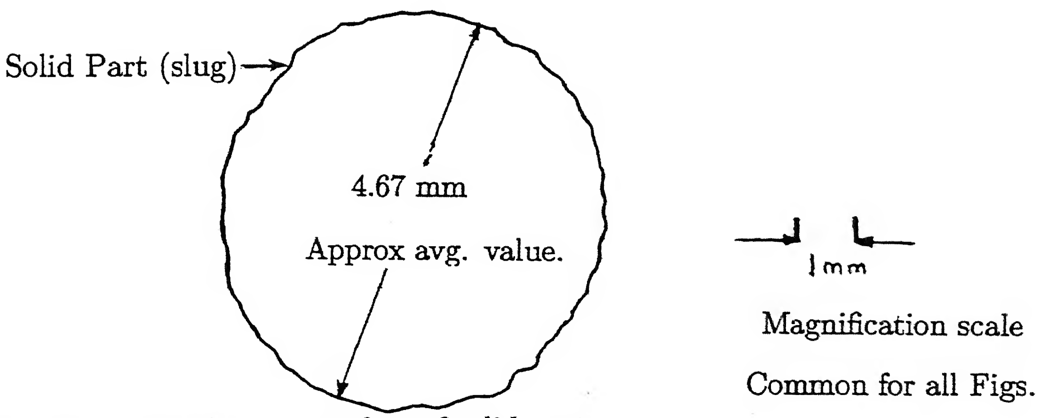


Figure 3.23: (Shadowgraph picture) Material : Alumina



Top view of the max. machined profile sample no. (22)



Top view of the bottom surface of solid part
which comes out due to trepanning action, sample no. (9)

Figure 3.24: (Shadowgraph picture) Material : Quartz

When the spark appears at the contact point between the tool and electrolyte, the heat generated is some what more uniformly distributed in Quartz (as compared to Alumina) over the entire workpiece material, which melts the material uniformly throughout the machined region.

The machined profile in the case of Quartz therefore, has less circularity error and less taper angle in comparison to alumina. Fig. 3.23 & Fig. 3.24 show the irregularities obtained on the machined profile in both the materials viz Alumina and Quartz.

3.3.1 Surface Integrity Of The Machined Profile

Various photographs of machined profiles, machined surface, and unmachined surface are taken by the scanning electron microscope (SEM). Surface irregularities, surface appearance and microcracks are also clearly visible. Study of machined surface by SEM is very encouraging. However, some problems are faced during the study i.e. focused surface get burned due to its non-conducting material property, so it can't be focused for long time at one particular spot. Also, before scanning the machined surface by SEM, it is vacuum coated with silver particle to make the machined surface conducting. Fig (3.25 - 3.31) shows the machined profile of different samples by SEM with the machining conditions shown in the table of Fig 3.1.

Fig. 3.25 (d) and (e) clearly show the material flow pattern which indicates that the material is being removed by melting.

Fig. 3.26 (c) and (d) show the X - section of the machined cavity. It clearly indicates lower MRR below the tool face as compared to the MRR on the sides of the tool edges. This is the main obstacle in achieving higher depth of penetration by ECSM process. Figure also shows thermally affected zone of the workpiece, Fig 3.27 also evidences that the machining is due to thermal phenomenon. Whitish

region indicates the area which has lower MRR than the dark area.

Fig. 3.26 (a) shows the full view of a machined part with the help of orbital rotation of tool. Fig. 3.26 (b), (c), & (d) shows further magnified view of machined surface showing the humb at the bottom of the machined surface. It is clearly understood from the figures that material is removed by the melting action, photographs shown at Fig. 3.26 (c) & (d) are taken from the through cracked sample.

Fig 3.28 (a) shows the full view of machined profile indicating the cracks developed during the machining, Fig. 3.28 (b) and (c) are showing the further magnified view of cracks appeared at machined zone.

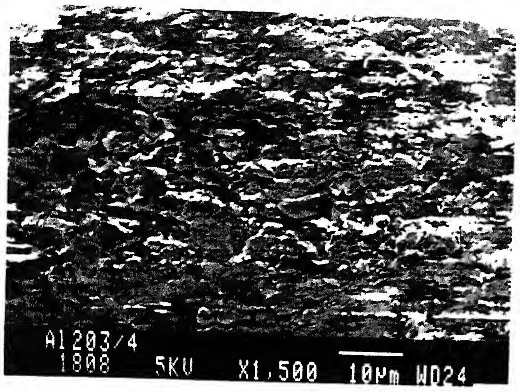
Fig 3.29 is showing the full view of machined surface in Quartz. In the part (a) of the Fig.3.29 unmachined surface (or slug) is shown at the center with bright appearance. Part (b) & (c) is showing the further magnified views of the machined part. Apart from melting mechanism, it also witnesses the random nature of the sparking locations resulting peaks and valleys in the machined surface.

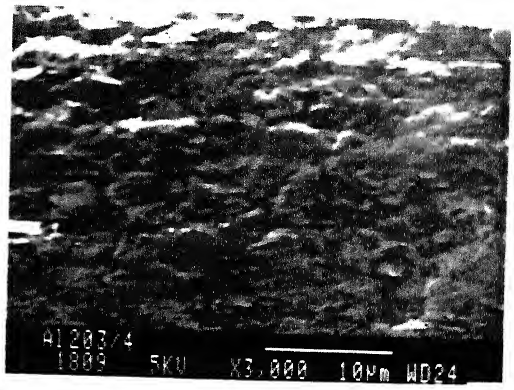
Fig 3.30 (a) is showing the full view of machined part (formation of hollow cavity, because center portion of the sample has come out due to trepanning action). Fig. 3.30 (b) & (c) are showing the magnified view of the machined zone indicating melted region.

Fig. 3.31 (a) shows the full view of solid part (or slug) which come out due to trepanning action of the tool. Part (b) shows the magnified view of the machined surface clearly indicating the melted region of the Quartz.

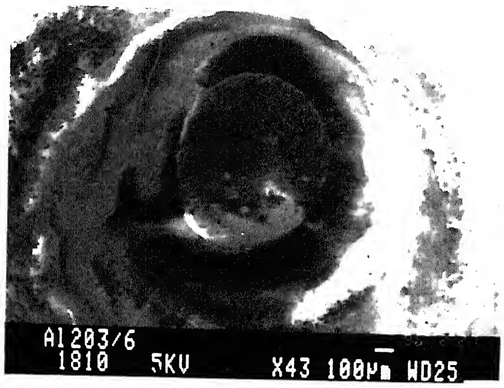
3.4 Study Of Inductor In ECD Circuit

The main motive for introducing the inductor in the circuit is to generates very high voltage pulses whenever there is a current pulse due to breakdown of the internal capacitance of the electrolyte. When the current starts to increase, the

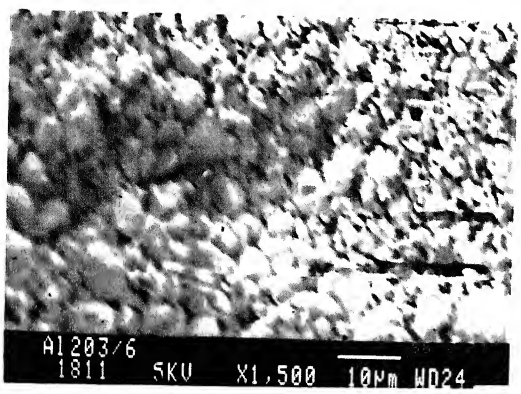


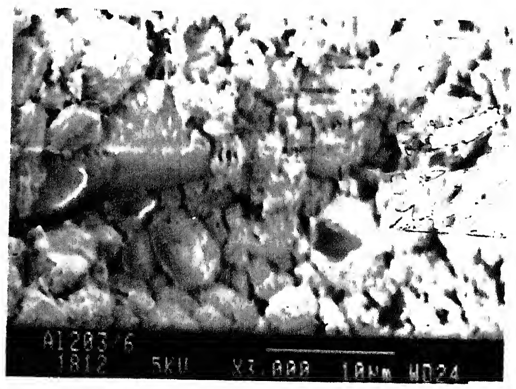


(a) Magnified view of unmachined surface. (b)



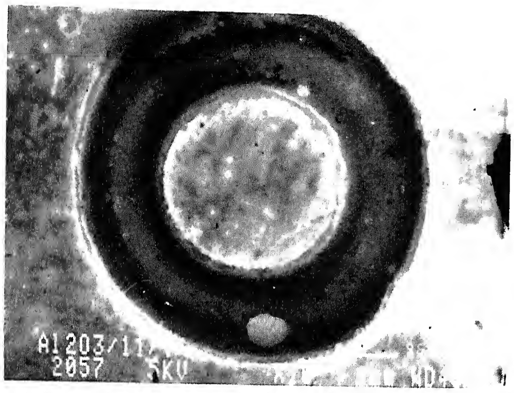
(c) Full view of the machined part by stationary tool.



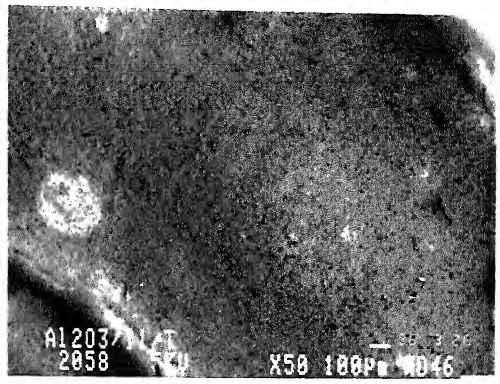


(d) Magnified view of the machined part (e)

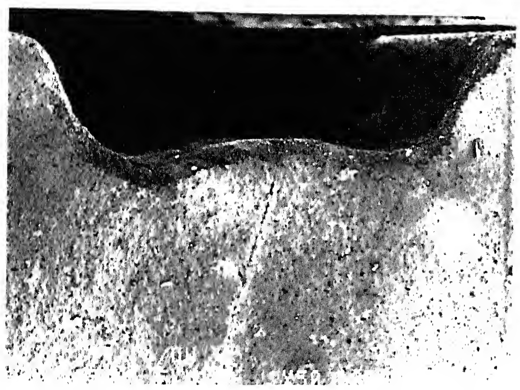
Figure 3.25: Material : Alumina



(a) Full view of the machined profile.

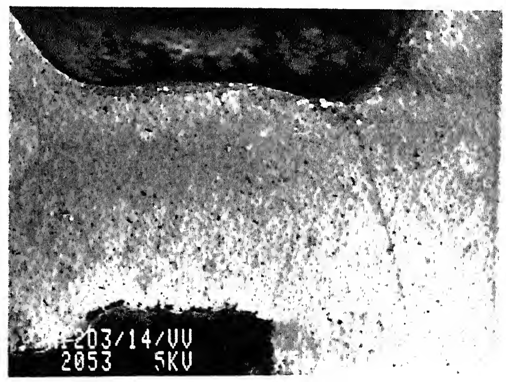


(b) Magnified view of the machined profile.



(c)

Leftside

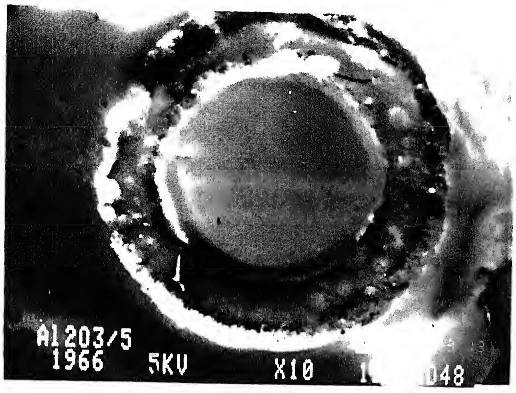


(d).

Rightside

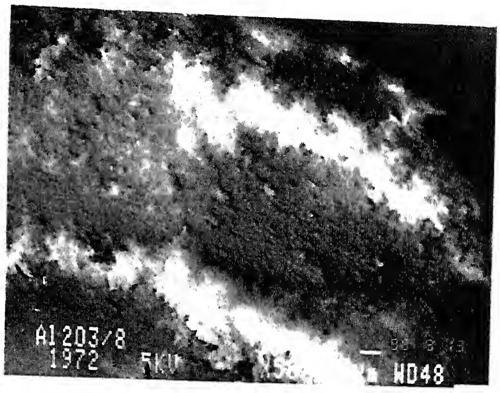
Magnified view of the cut - section of the machined surface.

Figure 3.26: Material : Alumina, sample no. 11



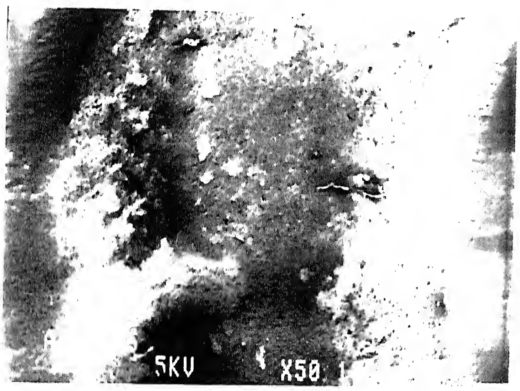
(a)

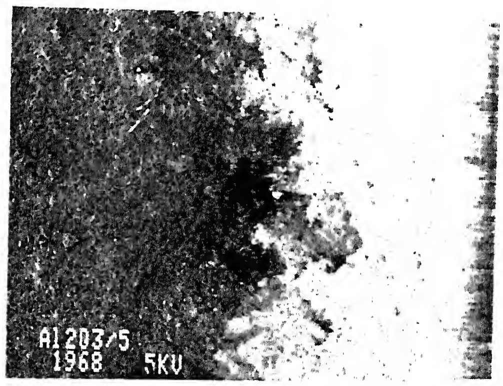
Full view of the machined profile next to max. machined surface.



(b)

Magnified view of the machined surface.

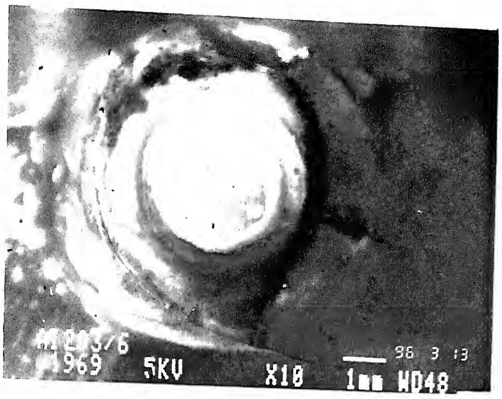




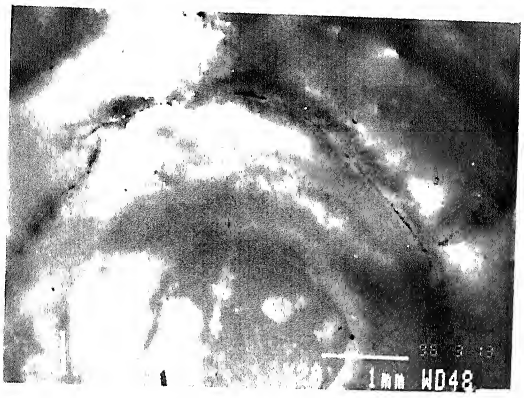
(c), & (d)

Further magnified view of machined surface.

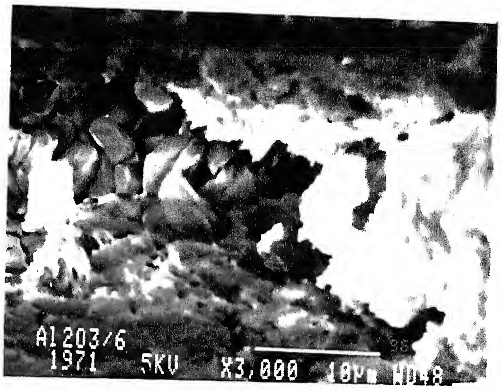
Figure 3.27: Material : Alumina, sample no. 5



(a) Full view of the machined profile
indicating cracks appear
during machining, sample no.(6)



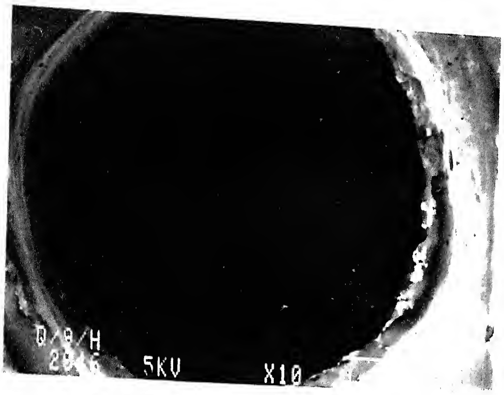
(b)



(c)

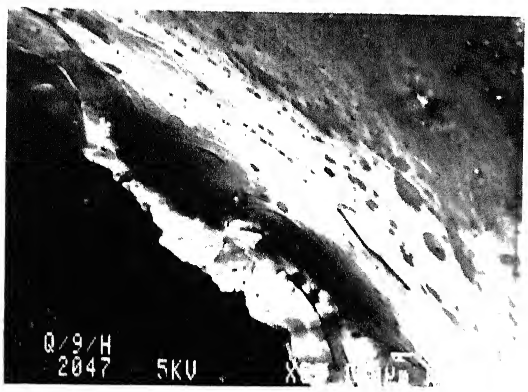
Magnified view of crack
appeared at machined surface, sample no. (6)

Figure 3.28: Material : Alumina, sample no. 6



(a)

Full view of machined profile
showing the hollow cavity
formed by trepanning action of tool.



(b) Magnified view of machined surface.

(c) Further magnified view of machined surface showing the details.

Figure 3.30: Material : Quartz, sample no. 9

(a)

Full view of solid part (or slug) which comes out due to trepanning action of tool.

(b)

Magnified view of solid part showing the melted portion.

Figure 3.31: Material : Quartz, sample no. 10

inductor generates an e.m.f. in the opposite direction, hence the voltage falls much below the supply value. As the current attains a maximum value ($dI/dt = 0$) the voltage attains the supply voltage. After this, the current starts to fall and hence the inductor starts to supply a voltage so that the resultant voltage is increased to arrest the fall of current [16].

Practically it is observed that the occurrence of spark in the electrolyte at low voltage is intermittent due to back emf produced by the inductor, which disturbs the gas layer at the electrode - electrolyte interface.[16] But when the smooth DC input voltage across the inductor is increased to a high value of 80 - 100 volts, a continuous bright spark appears around the tool surface dipped in the electrolyte. During machining of non-conducting materials by using inductor (62.54 mH) it is observed that due to high voltage pulses and high heat generated thermal shocks, workpiece material gets cracked. And also some time tool gets abruptly eroded from the tip. Therefore, practically it is not possible to do machining on ceramic like alumina at this stage by introducing an inductor.

Table 3.1 is showing the material removed, machined depth and overcut achieved in **Alumina**.

Table 3.2 is showing the material removed, machined depth and overcut achieved in **Quartz**.

The explanation for the typical behavior of machining performance affected by variable parameters viz electrolyte temperature and supply voltage is hypothesized in following manner :

The intensity of spark increases when the current drawn from the tool tip in-

creases due to increase in supply voltage and higher conductivity of the electrolyte, which is directly related to material removed and machined depth achieved upto certain limit[1].

But when the intensity of spark goes beyond this limit, melting of tool starts or in the other words we can say, the energy liberated from the spark partially goes to melt the tool and the remaining energy of the spark is utilized for eroding the workpiece material. Thus as we go for higher temperature and higher voltage, the contribution of heat energy to tool softening will be more in comparison to material removal from the workpiece, therefore machining rate will be reduced after a certain value of electrolyte temperature. Also the workpiece material shows the the cracking susceptibility due to high electrical pulses evolve from the high voltage spark.

3.5 Proposed Mechanism Of Material Removal In Alumina & Quartz

Material like Alumina whose melting point is very high of the order of 2050°C, get partially melt and etched by 50 - 70 volt range spark which appears at the tool tip in ECSM process. From the SEM observations it seems that grain get disconnected from the grain boundaries in the vicinity of spark from the workpiece material. The grain boundaries seems to be slightly etched from the machined surface. SEM photograph shows that material removal from the workpiece takes place due to melting as well as by etching process,[19].

In case of quartz whose melting point is 1600°C get easily machined because the temperature obtained at tool tip at 50 - 70 volt range is enough to melt the workpiece. From the SEM photographs the melted region of the machined surface is clearly visible Fig. 3.31.

[1]spark intensity beyond which tool starts softening

Machining on Al_2O_3 and Quartz by trepanning method to make a hole by gravity feed tool shows the oval shape at the bottom of the machined profile. Material removal mechanism shown in Fig (3.32) demonstrates the clear picture of ECSM.

Fig(3.32a) Shows that when the voltage is less than the spark voltage at the tool tip, it generates the non-conducting hydrogen gas bubble at the portion of the tool dipped in the electrolyte.

Fig(3.32b) When the voltage exceeds the critical voltage, the spark appears at the tool tip through the insulating gas layer.

Fig(3.32c) The tool electrode plays the role of electron supplier, at this time the electrolyte around the tool tip is heated by electron impact. As a result, ceramic material is etched off by the heated electrolyte.

Fig(3.32d) The removal of material continues with the trepanning action, which gets fresh electrolyte at every new position (trepanning action of the tool gives the stirring effect to electrolyte) and the material removal proceeds towards the area below the tool electrode.

Thus the material removal mechanism proposed for Al_2O_3 by ECSM process is based on etching effect of heated electrolyte and melting effect due to electrical spark appear at the tool tip. While the material removal from the Quartz is based on purely melting effect.

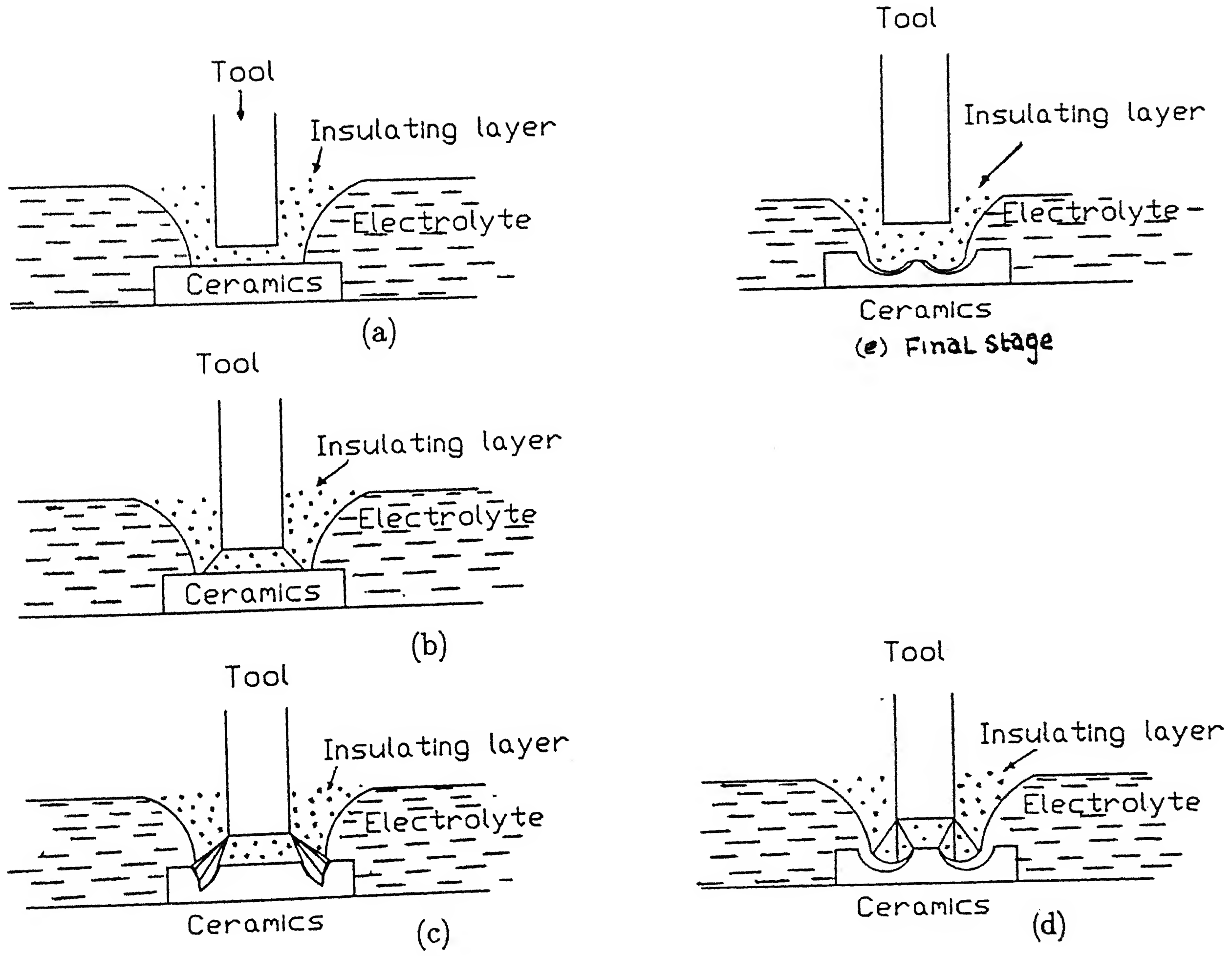


Figure 3.32: schematic diagram for material removal in Alumina

Table 3.1: Material removed, machined depth and overcut in Alumina

Temp. in ^0C	Supply voltage	Sample No.	Mat. removed in mg	Avg. Machined depth in mm	Diameteral overcut in mm
35	50	13	.9	.02	0.118
50	50	15	1.7	.03	0.305
65	50	17	3.9	.05	0.427
80	50	16	2.4	.03	0.415
35	60	8	13.2	.14	0.542
50	60	9	13.6	.13	0.577
65	60	2	20.4	.20	0.702
80	60	1	17.3	.14	0.827
35	70	12	36	.30	0.995
50	70	11	37	.30	1.028
65	70	7	47	.55	1.039
80	70	5	42.7	.46	1.004

Table 3.2: Material removed, machine depth and overcut in Quartz

Temp. in ^oC	Supply voltage	Sample No.	Mat. removed in mg	Avg. Machined depth in mm	Diameteral overcut in mm
35	50	1	53.2	.57	0.647
50	50	2	91.1	.92	0.747
65	50	3	140.2	1.50	0.891
80	50	5	109.4	1.19	0.808
35	60	6	158.8	1.56	0.732
50	60	4	173.8	1.82	0.775
65	60	8	199.3	1.89	0.983
80	60	7	178.9	1.73	0.812
35	70	21	369.6	2.89	1.497
50	70	20	381.1	2.88	2.110
65	70	19	559.8	4.13	1.977
80	70	22	576.7	4.21	1.842

Chapter 4

Concluding Remarks and Scope For The Future Work

4.1 Conclusion:

Results of the experiments are very encouraging and have shown the possibility of further improvement in the process performance by improving the design of the existing set - up. From the present work the following conclusions are made ;

1. Eccentric rotation of tool (trepanning action) with gravity feed has shown the improved performance related to machining (material removed, machined depth, circularity error and machining time) of non - conducting materials viz Alumina & Quartz.

2. The limitations associated with the ECSM process like limiting value of machined depth has been partially relaxed by using trepanning action of the tool electrode.

3. For the present configuration of the set - up it is seen that the improvement in the machining performance of the ECSM process halts after a critical value of temperature & voltage combination. May be higher proportion of spark energy is consumed in softening the tool.

4. Machining of brittle materials like Al_2O_3 and Quartz can be done at low voltage and low electrolyte temperature with trepanning action of gravity feed tool. At high voltage the Alumina specimens have shown the crack susceptibility.

5. SEM analysis has revealed that the quality of the surface obtained by the ECST operation is fairly good.

4.2 Scope For The Future Work

1. Machining with maintaining a few micron gap between tool electrode and workpiece can show the better machining performance. Use of efficient contact sensor can solve this problem.

2. Metal bounded abrasive tip tool can show much better machining performance. Because it can maintain the required gap between the tool and workpiece and simultaneously erode the material from the workpiece.

3. Pulsed power supply with the pulse time of the order of micro second can be used for increasing the material removal rate and improving surface finish.

4. Machining of non - conducting materials can be done more efficiently by keeping the minimum gap between the two electrodes, and if possible keep rotating the positive (+ev) electrode along with negative (–ev) tool electrode in the orbital path during machining.

5. Use of combination of electrolyte for the ECSM process is still an open field for research. Eutectic solution of NaOH and KOH has shown much better machining performance [6].

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APPENDIX : A

Mechanical Properties Of Alumina (Al_2O_3) [22].

Temperature in ^oC	Compressive St. in psi	Tensile St. in psi	Impact Res. (ln - lb)
25	560,000[1]	*	1.2
25	426,000[2]	*	*
30	*	37,600	*
300	*	36,400	*
400	213,000	*	*
800	185,000	34,000	1.0
1000	128,000	*	0.55
1050	*	33,800	*
1100	*	31,400	*
1200	71,000	18,500	*
1400	35,600	4,250	*
1600	7,100	*	0.32

1 : Zero porosity

2 : Less than 5% porosity

$\star$: Data is not available

Thermal Properties Of Alumina (Al_2O_3) [22].

Melting Point : 2051.0 ± 9.7^oC

Boiling Point : $3530^oC(3800 \pm 200^o\text{K})$

Temperature in ^oK	Thermal Conductivity (cal/sec cm^oC)	Sp. Conductance (cal/g^oK)
298	0.086	*
373	0.069	*
400	*	0.22545
500	*	0.24857
573	0.038	*
600	*	0.26372
700	*	0.27431
773	0.025	*
800	*	0.28205
900	*	0.28789
973	0.018	*
1000	*	0.29240
1100	*	0.29595
1173	0.015	*
1200	*	0.2987
1373	0.014	*
1573	0.014	*
1773	0.013	*
1973	0.014	*
2173	0.015	*

APPENDIX : B

Conductivity range for each test during experiment

Material : Alumina (Al_2O_3)

Voltage range : 50 - 70

Temperature in $^{\circ}C$	35	50	65	80
Voltage : 50				
Conductivity in mmho	(345 - 355)	(463 - 470)	(543 - 555)	(631 - 642)
Voltage : 60				
Conductivity in mmho	(344 - 353)	(461 - 469)	(541 - 549)	(630 - 641)
Voltage : 70				
Conductivity in mmho	(348 -357)	(459 - 465)	(545 - 552)	(628 - 642)

Conductivity range for each test during experiment

Material : Quartz

Voltage range : 50 - 70

Temperature in $^{\circ}C$	35	50	65	80
Voltage : 50				
Conductivity in mmho	(351 - 358)	(460 - 473)	(549 - 557)	(638 - 645)
Voltage : 60				
Conductivity in mmho	(353 - 360)	(462 - 475)	(544 - 552)	(640 - 648)
Voltage : 70				
Conductivity in mmho	(353 - 362)	(465 - 471)	(542 - 552)	(640 - 650)